



A review of recent advances in indirect evaporative cooling technology

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ABSTRACT

Indirect evaporative cooler with dew point cooling has great potential to replace the conventional mechanical vapor compression system in air conditioning industry. In this paper, a detailed review has been conducted on recent developments in the indirect evaporative cooling (IEC) systems as well as their associated design parameters and operating conditions for higher cooling effectiveness and cooling capacity. The current review also consolidates the design and performance of various indirect evaporative cooling systems (such as classical indirect evaporative cooler, regenerative, dew point cooler, and Maisotsenko cycle based cooler). **Furthermore, integration of these indirect evaporative cooling systems with other cycles is elaborated.** In addition, the thermal management potential of the indirect evaporative coolers in various applications is highlighted. **It is found that major design parameters include system configuration, inlet airflow conditions, channel geometry, and evaporative material. It is also found that counter-flow arrangement with higher inlet air temperature, lower inlet air humidity, smaller channel height, smaller inlet air velocity, higher channel length, and higher working to intake air ratio, triangular shape of channel with fabric evaporative material yields higher cooling effectiveness and efficiency.** This review indicates that the IEC systems could be a potential replacement for the conventional vapor compression cycle based cooling systems in buildings and other applications.

1. Introduction

Heating, ventilation, and air conditioning system has become necessity of people in both developed as well as developing countries. It accounts for 50% energy consumption in building sector, however in developing countries like China it accounted for 50–70% due to inefficient energy management system [1]. Currently mechanical vapor compression (MVC) systems are dominant over air conditioning industry. An intensive energy consumption and environmental issues are related to MVC. To overcome the energy consumption and environmental issues caused by emission of chlorofluorocarbons (CFC), it is

necessary to find the efficient, low power consumption, and environmental friendly systems for air conditioning purposes. In this regard, evaporative cooling system has gained growing interest from last decades because it offers high energy efficiency and is environmental friendly benign. Various indirect evaporative cooling systems have found potential applications in air-conditioning systems, gas turbines, electronic cooling, and cooling towers, and etc. [2]. Evaporative cooling is a novel technology that converts warm outside air into cool air by the latent heat of vaporization of water. Coefficient of system performance (COP) is much higher (15–20) than that conventional mechanical compression cycle system (2–4) [3]. The most commonly used

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evaporative coolers are direct evaporative cooler (DEC) and indirect evaporative coolers (IEC). In DEC, the product air comes in direct contact with water to facilitate latent heat of vaporization, hence the evaporation of water lowers the air temperature. This system effectiveness is very high but accompanies with increased humidity to yield possible thermal discomfort for occupants. To ease the influence of humidity, indirect evaporative cooling system is used. Significant amount of efforts have been made in the past and recent studies tend to investigate and optimize IEC using vertical plates with sprayed water [4–10], IEC using horizontal plates with atomized water [11–14], IEC using horizontal tubes [8,14,15], R-IEC using horizontal plates [11,16–18], R-IEC using vertical plates [9,18–23], and other evaporative cooling systems [24–30]. Besides, some innovative IEC systems comprising a thin aluminum foil have been developed that eliminate the need of hydrophilic surfaces [31]. Table 1 shows relevant researches upon IEC technology including conventional IEC, R-IEC, M-IEC, and D-IEC subject to different flow configurations such as counter, cross, parallel, and mixed flow, and different geometries such as plate, tube, and heat pipe. From the Table 1, most of the research was conducted on conventional IEC, R-IEC, M-IEC, and hybrid systems with cross flow configurations; followed by counter flow, mixed flow, and parallel flow. The detailed summary of the recent numerical and experimental studies on IEC systems will be provided in next sections.

Many reviews on evaporative cooling can be found in the literatures [3,8,35–43]. However, most of the reviews focused on direct evaporative cooling and their potential applications such as thermal management in solar systems, building applications, engines of motor vehicles, etc. To the best of our knowledge, the only review available in reporting the indirect cooling systems is by Duan et al. [14] who in 2012 reported that the continuous progress in technology innovation, particularly the M-cycle development and associated heat and mass transfer and material optimization, the IEC systems have obtained significantly enhanced cooling performance over those the decade. Yet more recently, there had been more devoted efforts on the development IEC. Hence, it is the purpose of this review to summarize recent advances (last three years in particular) on IECs as well as their integration with other applications in details in terms of their performance parameters, geometries and configurations (primary and secondary air flow direction), water distribution, and cooling capacity control strategies, etc. for various climates. Progress, prospects, and challenges are addressed elaborately.

Table 1
Scientific interest in indirect evaporative cooling systems.

Sr. #	System	Geometry	Flow configuration	Ref.
1	IEC	vertical plates	Cross flow	[4]
2	Multiple	Horizontal plates	Multiple cases	[11]
3	R-IEC	Vertical plates	Counter flow	[32]
4	R-IEC	Vertical plates	Counter flow	[19]
5	R-IEC	Vertical plates	Counter flow	[23]
6	M-IEC	Horizontal plates	Complex flow	[33]
7	IEC	Horizontal plates	Cross flow	[15]
8	IEC	Vertical plates	Cross flow	[5]
9	R-IEC	Horizontal plates with solar energy	Counter flow	[16]
10	IEC	Vertical plates	Cross flow	[6]
11	IEC	Horizontal plates	Cross flow	[12]
12	IEC	Vertical plates	Cross flow	[7]
13	M-IEC	Horizontal plates	Complex flow	[34]
14	R-IEC	Vertical plates	Counter flow	[22]
15	R-IEC	Multiple cases	Counter flow	[20]
16	R-IEC	Vertical plates	Counter flow	[18]
17	Multiple	Vertical plates	Counter flow	[9]
18	IEC	Vertical plates	Cross flow	[10]
19	R-IEC	Vertical plates	Counter flow	[21]

2. Fundamentals and working principles of evaporative cooling

Evaporative cooling can be divided into direct and indirect types. Direct evaporative cooling (DEC) makes use of enthalpy of vaporization to raise the humidity (up to 70 to 90%) while reducing the dry bulb temperature. Typical DEC follows isenthalpic process alongside the psychrometric chart. To sustain the evaporation process, the humidified moist air should be constantly removed to the ambient. A mechanical direct evaporative cooler (M-DEC) as shown in Fig. 1(a) accommodates appreciable wetted membranes or pads as the surface area which can enhance water evaporation rate considerably. However, for the passive direct evaporative cooling (P-DEC) units that do not employ any auxiliary fans, evaporation process takes place with the help of a fountain or a passive cooling tower. The cooling tower draws the outside air over the top of a tower, which is built inside or next to the building. Direct evaporative cooling is an open circuit process. Indirect evaporative cooling is a closed circuit process. This employs the direct evaporative cooling plus a heat exchanger for the cooling purpose. The moist air from the direct evaporative cooling (DEC) makes a direct contact with the conditioned supplied air as depicted in Fig. 1 (b). The moist air is released to the ambient or cools by some external devices like solar cells. In this way, excess humidity is prohibited in enclosed spaces such as residential systems. Some of the potential applications of IECs including buildings are illustrated in Fig. 2. The potential applications include both human and non-human thermal comfort. Most of the studies included in the present review are related to the thermal comfort of human whereas very few studies [44–46] regarding the applications of evaporative cooling in thermal management of livestock, poultry birds, and agricultural storage applications have been included in this study. The authors have assessed the potential of various evaporative cooling systems in applications like agricultural storage, poultry birds, and livestock.

2.1. Recent advances in indirect evaporative cooling

For the last three years, numerical and experimental studies on indirect evaporative cooling technology are extensively conducted as depicted Table 2 and Table 3. These two tables highlight the recent studies in terms of the system design and their major findings. It can be seen that most of the numerical and experimental work is on performance improvement for different climates by optimizing the geometric parameters and flow configurations for various IEC systems such as classical, regenerative, M-cycle based, and dew point cooler. Besides, integration of the IECs with other cycles has been extensively investigated. Furthermore, effect of various performance parameters such as condensation along with system configuration (plate, tube, heat pipe, rotary wheels, etc.) has been remained the topic of the interest for the researchers. The detailed discussion of the recent advances in IECs will be provided in the next sections.

Table 2 provides a detailed summary of the numerical works performed recently.

Based on the forgoing literature review, indirect evaporative coolers can be classified as conventional, regenerative, dew-point, and Mal-sotsenko cycle based (M-cycle) cooling systems. Besides, IECs can be combined with direct evaporative cooling or other cycles to form hybrid systems for further performance improvement. A classification of evaporative cooling systems is given in Fig. 3. The details of each indirect evaporative cooling system as well as its integrated systems will be given in the following sections.

3. Classical indirect evaporative cooling (IEC) and its integration with other cycles

In indirect evaporative cooling system, air can be cooled without introducing moisture content. In IEC, there are two separate channels for primary and working air. The primary air in dry channel is sensibly

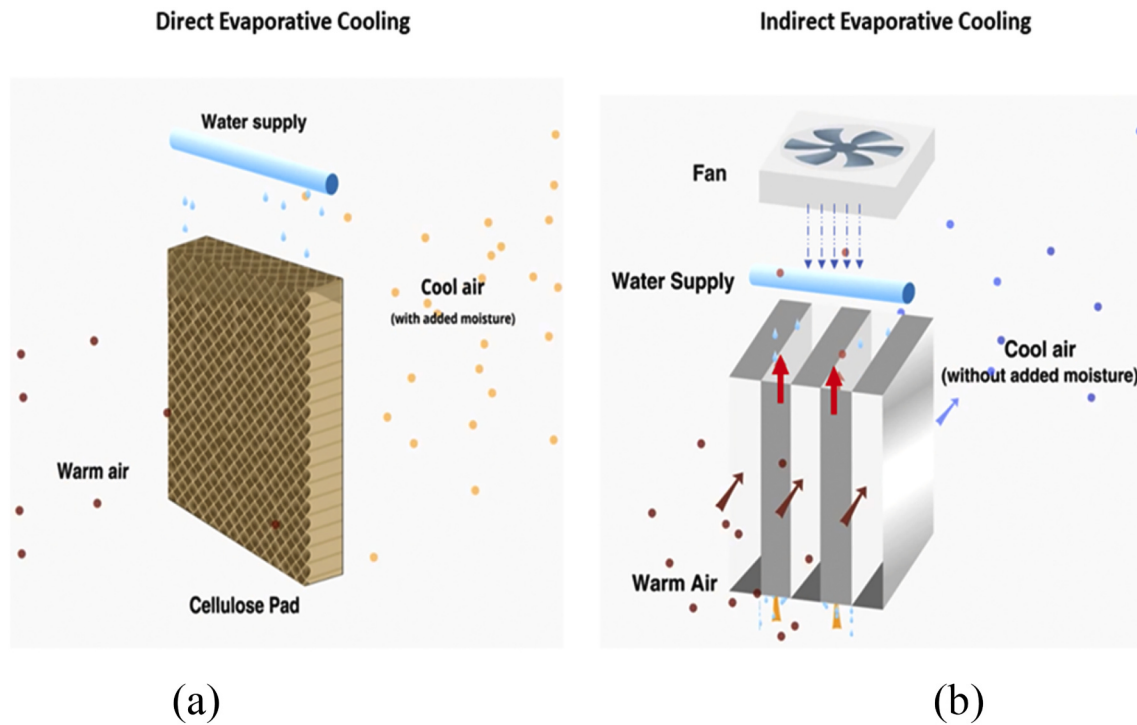


Fig. 1. (a) Direct vs (b) indirect evaporative cooling.

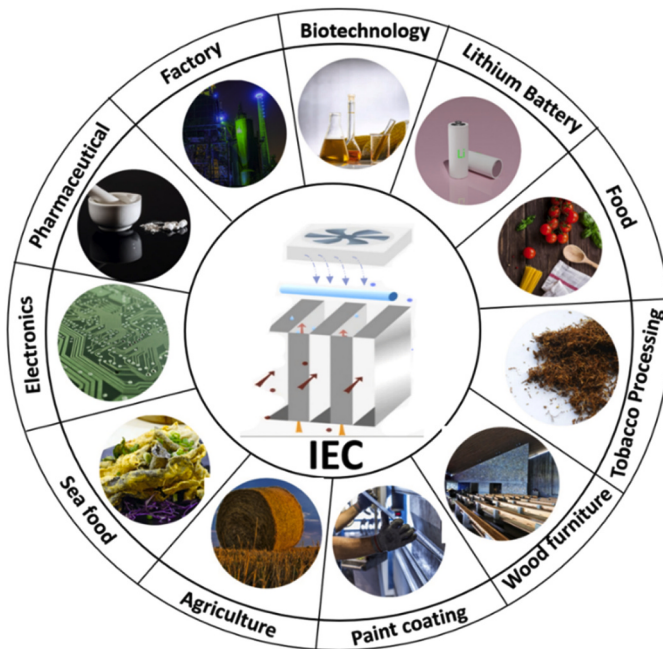


Fig. 2. Applications of indirect evaporative cooling systems.

cooled by the working air, which is cooled by the evaporation of water in wet channel. The working principle of wet channel is similar to DEC where the working air is in direct contact with water. Without moisture exchange between these two channels, the humidity of primary air stays unchanged. The theoretical limit for the cooling of primary air is the wet bulb temperature of inlet ambient air but typically can reach only 50–80% wet bulb effectiveness [3].

Practitioners are more interested to know about the output conditions of a cooling system rather than the detail of the process. For this purpose, various studies have been conducted to predict and analyze the

performance of various general counter-flow IECs. In line with this, Wan et al. [83] proposed a simplified method to realize an optimum design of a dew-point evaporative cooler. In another study [84], some regression models were proposed to predict the performance of counter-flow dew-point evaporative coolers. Pandelidis et al. [85] numerically examined the performance of various counter-flow IECs and concluded that their proposed novel IEC is able to achieve quite low outlet temperature along with higher cooling capacities. An added benefit is its controllable air handling unit. As a result, the proposed unit can well reduce the energy consumption in air conditioners integrated with IECs. Besides, it has capability to be operated as a heat recovery unit in winter.

IEC systems have been integrated with many applications such as humidification-dehumidification cycle (for desalination), fresh air-handling units, air conditioning systems, heat recovery, etc. The working principle of various indirect evaporative cooling (IEC) systems such as stand-alone indirect evaporative cooling system, indirect evaporative cooling system integrated with direct expansion cooling unit, indirect-indirect evaporative cooling systems, and indirect/direct evaporative cooling systems is represented in Fig. 4. As known, various IEC systems are categorized based on the limit of the cooling provided, their potential to remove the moisture contents in the supply air (e.g. whether they can humidify/dehumidify the supply air), and flow configurations.

An investigation of various evaporative coolers including IEC (conventional indirect evaporative cooler), IEC using outside air, DEC (direct evaporative cooler), DEC + IEC (hybrid cooler consisting IEC and DEC), and DEC + IEC using outside air in the climatic conditions of Poland was carried out [74] (see Fig. 5). Besides, a system without any adiabatic dehumidification was analyzed as a reference. The investigated systems can be categorized on the basis of their configurations. These systems confirm IEC and IEC alternatives reveal energy saving potential. In particular, the combined direct and indirect evaporative cooler that uses just outside air for dehumidification, shows the greatest potential. It was also concluded that cooling systems replacing the exhaust air with outside air for the dehumidification are highly efficient and can further reduce the indoor air temperature (see Fig. 5c and Fig. 5f). It should be kept in mind that system without any adiabatic dehumidification has SCOPs (seasonal coefficient of performance) equal to zero. This is

Table 2

Recent numerical studies on the indirect evaporative cooling (Years: 2018–2020).

Ref.	System type and climate	Application	Major findings
[47]	IEC different climates		A First-Principle Data-Driven model for IEC (indirect evaporative cooling) and a MATLAB-based simulation study mimics some thermal aspects of the IEC process. The investigation is time and cost saving.
[48]	R-IEC different climates		The numerical investigation suggests that improved sustainability index and exergetic efficiency along with reduced CO ₂ emission can be achieved by lowering the airflow rate, channel gap, and extraction ratio. Besides, some optimal configurations are suggested.
[49]	Dew-point IEC (Counter-regenerative & cross configurations) different climates	Cooling of small residential buildings	A multi-objective optimization suggests the counter-regenerative configuration to be the best choice for hot and arid regions while the cross configuration for other climates. The optimal configurations demonstrated an improvement of 86.4, 64.4, and 1039.0% in the annual water consumption, life-cycle cost, and the annual average of the COP, respectively.
[50]	Counter-flow IEC with conventional recuperator HX heat recovery temperate climatic conditions	Integrated with air conditioners	The potential of a counter-flow IEC as a heat recovery device in air conditioners was evaluated under in the temperate climate by using ε -NTU-model. It was shown that this modified system is much more energy efficient than that of the conventional recuperator. Besides, the proposed system can acquire substantially higher temperature drop compared to the conventional recuperators.
[51]	Dew-point IEC with optimized air and water flow arrangement	Replacing commercial D-IEC system	The proposed D-IEC system showed an improvement in the COP and wet bulb efficiency up to 34.6% and 29.3%, respectively than that of the commercial D-IEC of same capacity. The numerical findings indicate that the structure of the cooler has a strong

Table 2 (continued)

Ref.	System type and climate	Application	Major findings
[52]	IEC	Performance evaluation	influence on the cooling rate. Furthermore, an ideal flow arrangement with 62%–67% higher energy saving potential was suggested. A heat current model was developed to find the optimal design by introducing a new parameter known as moisture-temperature ratio. This ratio unifies the humidity and temperature differences to express the heat and mass transfer together.
[53]	Hybrid HVAC system with a desiccant wheel and IEC different climate zones	buildings with elevated latent loads	An efficient and economical hybrid system consisting desiccant wheel integrated with IEC was proposed as an alternative to the conventional (direct expansion) systems. The numerical results showed that the DW-IEC was able to achieve up to 46.8% energy savings (higher COP), far more than the conventional system.
[54]	Hybrid Indirect Evaporative Pre-cooler (Integrated) different climate zones	IEC integrated with air conditioner	A hybrid air-conditioner integrated with IEC (pre-cooler) is proposed, which employs the exhaust air from the room to pre-condition the intake ambient air via IEC. It was found that the IEC as a pre-cooler possess the noticeable energy saving potential.
[55]	R-IEC with a novel temperature control Transitional and other seasons	Cooling of buildings	A novel high-low control (H-L) strategy is compared with the conventional on-off control. The findings reveal the superior performance of H-L control mode in terms of thermal comfort, energy saving (11.3% higher than on-off control), and indoor air-quality.
[56]	Co-current DEC and cross flow IEC integrated different climates	Cooling of buildings	A finite difference method (FDM) was used to optimize the geometric and operating parameters for ECs. The cross-flow IEC and co-current DEC demonstrated the highest efficiencies i.e. 40% and 73%, respectively. Hence, these two designs were suggested to be used together.
[57]	Cross-Flow R-IEC	Replacing the conventional HMX (heat and mass exchanger)	From the numerical analysis of two IECs, it was shown that for stand-alone HMXs, the R-HMX

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Table 2 (continued)

Ref.	System type and climate	Application	Major findings
			is better than conventional HMX at low supply airflow rates. In multistage evaporators, for high supply airflow rates, the conventional HMX is more beneficial during the first stage (as a pre-cooler) whereas the R-HMX is suitable during the second stage (as a re-cooler).
[58]	M-IEC integrated with air conditioner Humid	air-conditioning of the buildings	M-cycle as a cooler of recirculated air integrated with a refrigeration system with heat recovery could save more energy than M-cycle as a pre-cooler of the external air integrated with a refrigeration system.
[59]	Novel high-performance D-IEC (DPC) integrated with an HMX all kinds of climates	Cooling of buildings	A numerical study presents a novel, highly efficient D-IEC (dew point cooler) integrated with an unguided and corrugated HMX. The close performance predictions of the model against the experimental data manifests its potential as an effective and efficient approach to model the optimized evaporative cooling systems for a wide range of operating conditions and buildings.
[60]	Plate, cross flow, IEC, condensation-ratio hot and humid environments	integrated with air conditioners for supply of fresh cool air	A 2D mathematical model (with an error of 8.6%) was developed for a plate crossflow IEC taking into account the condensation ratio. MATLAB and Finite difference method have been used for various states of condensation such as total condensation, partial condensation, and no condensation.
[61]	R-IECs Different ambient conditions	Performance evaluation, comparison	The parallel/cross flow in wet channels are suggested to be the best for most of the investigated operating conditions.
[62]	IEC with condensation	Correlation development	A numerical analysis showed that both Nusselt number and Sherwood no. under the existing conditions are higher compared to these numbers under constant heat flux and surface temperature conditions. The developed simplified correlations can be a good reference for the IECs experiencing condensation.

Table 3

Recent experimental studies on the indirect evaporative cooling (Years: 2018–2020).

Ref.	System type and climate	Application	Major findings
[63]	An integrated IEC and humidification-dehumidification desalination cycle dry and hot areas	Freshwater and cooling	An IEC integrated with a humidification-dehumidification desalination cycle can lower the supply air temperature below 25 °C and a reduction of 5–10 °C in purge air temperature can be achieved.
[64]	R-IEC Integration of heat pipe and porous ceramic tube (alternative to plate HX) arid climates	cooling of buildings	A novel regenerative evaporative cooler (R-IEC) unit is proposed, in which integrated porous ceramic tube and heat pipe replace the plate HXs. Under laboratory testing conditions, COP and cooling capacity up to 11.43 and 140 W/m ² , respectively are reported. Under certain environmental conditions, up to 14 °C reduced (below ambient air) supply air temperature is achieved. The proposed IEC (fresh air handling unit) in hot climates was able to reduce the unit's cooling capacity up to 43% for indirect evaporation as compared to dry operating mode. Three configurations namely cross, advanced multi-zonal and counter heat and mass exchangers are investigated to improve the seasonal employability of an IEC integrated air-conditioner. The seasonal utilizability factors of cross, counter, and multi-zonal IEC systems were reached up to 1.13, 1.41, and 1.34, respectively. The proposed IEC systems demonstrated outstanding performance in semi-arid areas and deserts. In the proposed hybrid system, desiccant and heat recovery wheels are coupled with M-IEC system. MC-DAC system showed up to 60–65% higher COP _{th} at low regeneration temperatures under
[65]	IEC hot climates	fresh air handling unit	
[66]	Waste energy recovery in an IEC Semi-arid, deserts, and other climates	IEC integrated with A/c	
[67]	Cross flow M-IEC Different inlet air/water conditions	Integration with desiccant and recovery wheels	

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Table 3 (continued)

Ref.	System type and climate	Application	Major findings
[50]	Counter-flow IEC temperate climate	Heat recovery	same supply air scenarios. The potential of a counter-flow IEC as a heat recovery device in air conditioners was evaluated in temperate climate. The retrofitting conventional recuperator exchangers could be converted into efficient IECs. The modified system could save far more energy than that of the conventional recuperator in temperate climates. Conditions. Moreover, this counter-flow IEC could significantly increase the temperature drop during heat recovery process compared to the conventional recuperators.
[68]	Water-spraying in IEC	Energy recovery IEC	Three water spray-modes namely internal spray, external spray, and mixed spray (internal-external) on the efficiency of a particular ventilation energy recovery IEC were experimentally investigated. The mixed mode was found to be the best while the external mode was the worst with respect to cooling capacity, the COP, and the wet bulb efficiency. By enhancing the wettability, the performance of the mixed mode was further improved.
[69]	Two-stage DEC-IEC Hot climates	greenhouse applications	A two-stage DEC-IEC was proposed for greenhouse applications. Hybrid systems equipped with effective could maintain the desired humidity and temperature within the greenhouse, particularly in hot climates.
[51]	D-IEC (Dew-point IEC with optimized air and water flow arrangement)	Replacing the commercial D-IEC	A highly efficient D-IEC with optimal water and airflow scheme was reported, which showed an improvement in the COP and wet bulb efficiency up to 34.6% and 29.3%, respectively than that of the commercial D-IEC of same capacity.
[53]			

Table 3 (continued)

Ref.	System type and climate	Application	Major findings
	A hybrid system with a desiccant wheel and an IEC Hot climates	HVAC in buildings with elevated heat loads	A hybrid system consisting desiccant wheel integrated with IEC was proposed as an alternative to the conventional (direct expansion) systems in order to achieve comfort conditions in the buildings with elevated latent loads. The proposed system is economical and efficient.
[54]	Hybrid Indirect Evaporative Pre-Cooling System various climates	Integrated with air conditioners	A hybrid air-conditioner integrated with IEC (pre-cooler) is proposed for various climates, which employs the exhaust air from the room to pre-condition the intake ambient air via IEC. The IEC as a pre-cooler shows the noticeable energy saving potential.
[70]	Cross-flow IEC with condensation	Performance evaluation	From the investigation of a cross flow IEC with condensation, it was concluded that condensation caused an improvement in heat transfer, outlet temperature of primary air, and water consumption. The disadvantages are the lowered wet bulb effectiveness and increased thermal resistance of the condensate due to thick water film.
[71]	Counter flow plate HX combined with ultrasonic atomizer humid and hot environments	Enthalpy recovery	A counter flow plate HX integrated with an ultrasonic atomizer was proposed and investigated as an IEC based enhanced enthalpy recovery method. Comparatively enhanced cooling effect caused by the ultrasonic atomizing is due to increased area of water mists and reduced thermal resistance between the supply and exhaust air streams. There is no contaminant transfer from exhaust to supply air. This is because no sorption or mass permeation, or carry-over occurs during the heat exchange. The experimental findings in humid and hot environments reveal a 71% achievement in heat recovery efficiency while the supply-air

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Table 3 (continued)

Ref.	System type and climate	Application	Major findings
[72]	Parallel, counter, and cross flow IEC	Performance evaluation	moisture condensation caused almost 50% recovery of the enthalpy. An efficient design to promote the water distribution is developed. The plate geometry has a strong influence on the heat transfer and surface wettability. A protrusion of reticular plates tends to be a successful solution to increase the effectiveness of the device. Compared to the counter flow arrangement, the parallel water and secondary air flows configuration results in increased wet bulb efficiency and reduced pressure drop.
[73]	Indirect air cooling system combined with evaporative cooling cycle (IAC + EC) humid, sub-humid, and hot climates	storage applications	The proposed design showed comparatively higher energy saving potential (low temperature and high RH of the new system compared to the ambient) for storage applications in humid, sub-humid, and hot climates.
[74]	DEC + IEC	dehumidification	The hybrid DEC + IEC system using outside air for dehumidification, shows a great potential. The cooling systems replacing the exhaust air with outside air for the dehumidification are highly efficient and can further reduce the indoor air temperature.
[75]	Plate, IEC	Evaluation criteria	A new evaluation index namely the enthalpy index was introduced and used to plate counter flow and cross flow IECs. With the help of the new index, the heat transfer capacity of the IECs can be evaluated. Besides, it can be employed for selecting the equipment design, optimizing the performance, and performing the thermal calculations for an IEC.
[76]	IEC integrated with an inverted Brayton cycle Different inlet conditions	waste-heat recovery	An IEC integrated with an inverted Brayton cycle is proposed to improve the performance for waste heat recovery. This system introduces the pre-conditioned working fluid to the

Table 3 (continued)

Ref.	System type and climate	Application	Major findings
[77]	Water spraying in IEC Different conditions	Performance optimization via wettability control	compressor inlet. The proposed system showed up to 45% improvement in the specific work output regardless of air inlet condition and turbine inlet temperature. Very high thermal efficiency was realized for the heat source temperature less than 85 °C. Water spray strategies and the nozzle types greatly affect the wetting conditions of the wet channels. An investigation has been conducted to homogenize the water film distribution inside the IECs via introduction of some novel materials. The spiral type nozzles are affirmed as the optimal design for IEC systems due to their better uniformity and prominent coverage ratio.
[78]	DEC-IEC using a straight heat pipe Different conditions	Evaluation of multi-stage IEC systems	The performance of a multistage DEC-IEC with a heat pipe is evaluated. Heat pipes are employed in the first (to pre-cool) and third stages (for indirect cooling). Two stages together (first and second) can alleviate the saturation efficiency although the RH of the outlet air and the water consumption are increased. The maximum reduction in temperature was achieved during the 1st stage when evaporation takes place. It was also observed that three stages yield a minute reduction in RH and temperature.
[79]	Porous ceramic tube type IEC	Wettability control	One of the effective way to improve the performance of the IECs is via wettability control of the wet channels by using porous ceramic tube. The porous structure of the tube offers water-storage capacity and hydrophilicity, which in turn improve the wet bulb efficiency of the cooling unit. The findings point out the optimal tube spacing (40 mm). The

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Table 3 (continued)

Ref.	System type and climate	Application	Major findings
[80]	IEC with primary air condensation	Performance evaluation (condensation effect)	length of the tube under 1.5 m has a remarkable influence on the IEC performance. An optimal porous ceramic design has working air and product air velocities as 4.0 m/s and 3.4 m/s while the working air volume ratio as 0.9.
	hot and humid regions		In hot and humid regions, an IEC as a pre-cooler and pre-dehumidifier could be utilized as an effective tactic by apprehending the cooling potential of exhaust air coming from the air-conditioned indoor environment. The retaining condensate in the primary channels has a serious influence on thermal performance of IEC. Moreover, the inlet primary-air conditions (temperature and RH) have a profound impact on the heat transfer (condensation) performance of the system. The dropwise condensation should be promoted to improve the performance of air conditioners.
[81]	IEC with refrigerator	Precise temperature control in multi-compartment domestic refrigerator	An effective system for precise control of cooling capacity delivery in MIR (multi-compartment indirect cooling domestic refrigerator) is proposed by introducing a novel air distributor along with a variation in the position of air-supply dampers in the distributor.
[82]	Direct-Indirect DEC-IEC	fresh air handling unit	During the water shower mode, DEC-IEC system achieved a maximum temperature drop of 18.8 °C at an ambient T_{wb} of 44 °C and RH less than 20%. An increase in RH generally reduces the temperature drop across the HX during the (a) water shower and (b) combined water shower and mist injection modes.
	Hot climates		

because of lack of cooling possibilities in the system.

3.1. IEC integrated with humidification-dehumidification desalination (HDH) cycle

As freshwater and cooling are two essential demands in dry and hot areas. In line with this, IEC and humidification-dehumidification desalination (HDH) systems are integrated [63]. This system supplies the divided airstream from IEC into HDH. The proposed cycle along with its psychometric representation is shown in Fig. 6. Humidity and the temperatures of the vented air are achieved by a pilot IEC setup. The experimental findings reveal that the temperature of the supply air can be lowered below 25 °C to achieve a temperature reduction of 5–10 °C relative to the intake airflow. An analytical investigation of the HDH system is performed by using this purge air as the working fluid and it is found that up to 25–125 L/h of freshwater can be produced. It is to be noted that under same operating conditions, these results are higher than other HDH systems. The overall COP (coefficient of performance) of the integrated IEC-HDH system is found to be 2.1 to 2.5. Further improvement in efficiency could be made available by integration with vapor compression refrigeration or adsorption cycles.

3.2. IEC as a fresh air handling unit (dual system)

There were some researchers carrying out experimental study to evaluate IEC (fresh air handling unit) in hot climates in association with various operating modes. The different operating modes were obtained by some pretreatments such as water shower, mist injection, or combining the water shower and mist of the secondary air stream. The unit's cooling capacity was reduced up to 43% for indirect evaporation as compared to the dry operating mode. It can be concluded that the performance is a function of the ambient conditions as well as operating mode of the FAHU. A particular operating mode may offer improved performance in a certain ambient condition but could behave poorly in other condition. Another study has been performed to improve the seasonal applicability of an IEC integrated air-conditioner [66]. Three different arrangements namely cross, counter, and multi-zonal for IEC have been employed and investigated as shown in Fig. 7. The waste heat from the wet air passages is recovered to produce comfort dry air that is supplied to the human occupants. Thus, this improved design operates for dual purposes.

Three configurations namely cross, advanced multi-zonal and counter heat and mass exchangers are investigated with respect to their energy-efficiency ratio, system capacity, and mixing ratio. The seasonal utilizability factors of cross, counter, and multi-zonal IEC systems were reached up to 1.13, 1.41, and 1.34, respectively. Furthermore, these IEC systems demonstrated outstanding performance in semi-arid areas and deserts. The performance of a DEC-IEC fresh air handling system has been assessed in different operating modes (water shower, mist injection, and a combination of the water shower and mist injection mode). During the water shower mode, a maximum temperature drop of 18.8 °C is noted at an ambient T_{wb} of 44 °C and RH less than 20%. An increase in RH generally reduces the temperature drop across the HX during the (a) water shower and (b) combined water shower and mist injection modes. Moreover, the water consumption is positively correlated with T_{DB} while is negatively correlated with ambient RH. The lowest energy consumptions for the water shower and mist injection modes were 1.64 and 1.89 kWh, respectively at peak T_{DB} . At the same operating conditions, this value for the combined water shower and mist injection operating mode was found to be 2.7 kWh at peak T_{db} . The multi zonal arrangements of dew-point IEC were originally proposed and patented by Pandelidis et al. [86]. The designed IEC arrangements demonstrated higher cooling efficiency compared to the original cross-flow M-Cycle heat and mass exchangers (HMXs). In addition, the proposed HMXs could simultaneously attain lower supply air temperature along with higher cooling capacity.

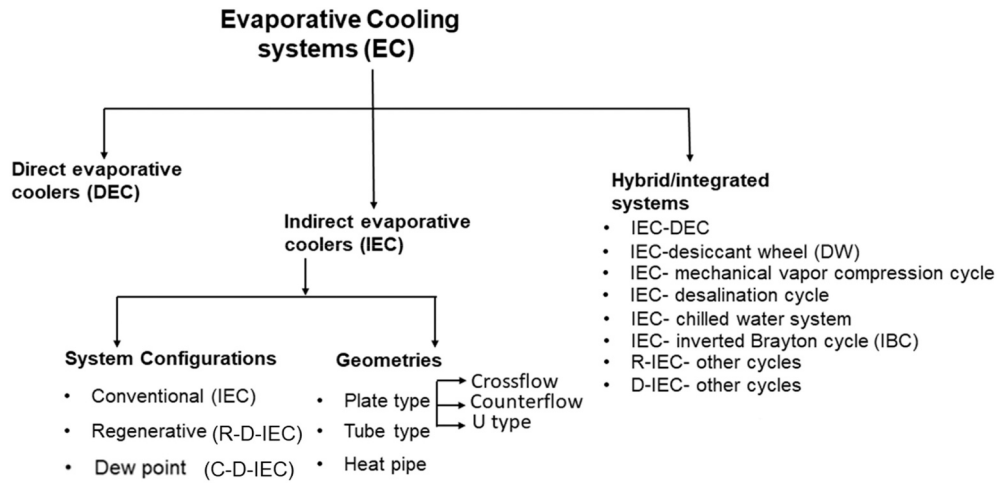


Fig. 3. Classification of evaporative cooling systems.

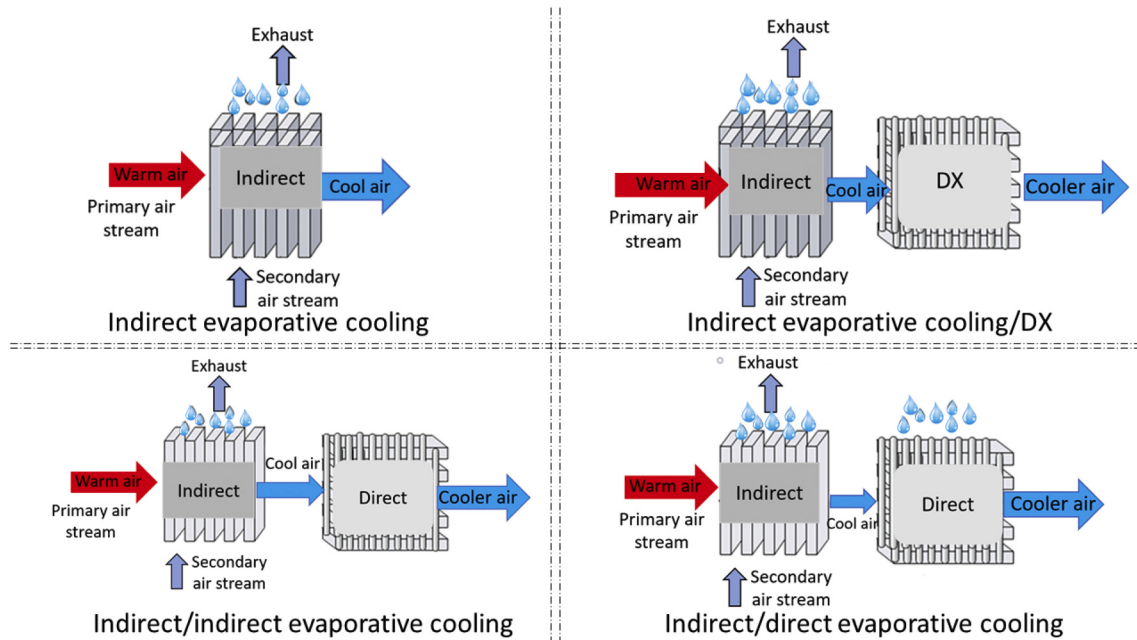


Fig. 4. Working principle of various IECs and integrated cooling systems.

3.3. Below dew-point indirect evaporative coolers

D-IECs allow to cool the air below wet bulb temperature whereas the typical IECs do not allow cooling below the wet bulb temperature. Below dew-point evaporative coolers are used for the energy recovery. In these systems, the treated air can be cooled below its dew-point temperature. Feasibility study regarding the potential of a counter-flow IEC as a heat recovery device in air conditioners was evaluated under summer time where temperature and humidity ratio is less than 32 °C and 15 g/kg, respectively [50]. The proposed system was investigated in different condensing states such as no condensation, partial condensation, and total condensation (see Fig. 8). It was found that the occurrence of condensation alongside the channel of product air imposes a significant influence on the outlet airflow parameters and the performance of the IEC-HMX.

They [50] showed that the retrofitting conventional recuperator exchangers could be converted into efficient IECs. It was also shown that this modified system could achieve significantly higher performance indicators than that of the conventional recuperator under the climatic

conditions. Moreover, this counter-flow IEC could significantly increase the temperature drop during heat recovery process compared to the conventional recuperators. Yet, recovery of water condensate from OEC is also feasible. However, it needs additional pumping power to overcome the pressure drops.

Water can partially replace the refrigerant in IECs and can be used as energy recovery ventilation or stand-alone cooling system [68]. IEC efficiency and performance greatly depends on the water circulation over the plate walls. Three water spray-modes, including internal spray, external spray, and mixed spray (internal-external) on the efficiency of a particular ventilation energy recovery IEC were experimentally investigated. The mixed mode was found to be the best while the external mode was the worst with respect to cooling capacity, the COP, and the wet bulb efficiency. By enhancing the wettability, the performance of the mixed mode was further improved. A counter flow plate HX integrated with an ultrasonic atomizer was proposed and investigated as an IEC based enhanced enthalpy recovery method [71]. An illustration of the principle and psychrometric process of the proposed total heat recovery system is given in Fig. 9.

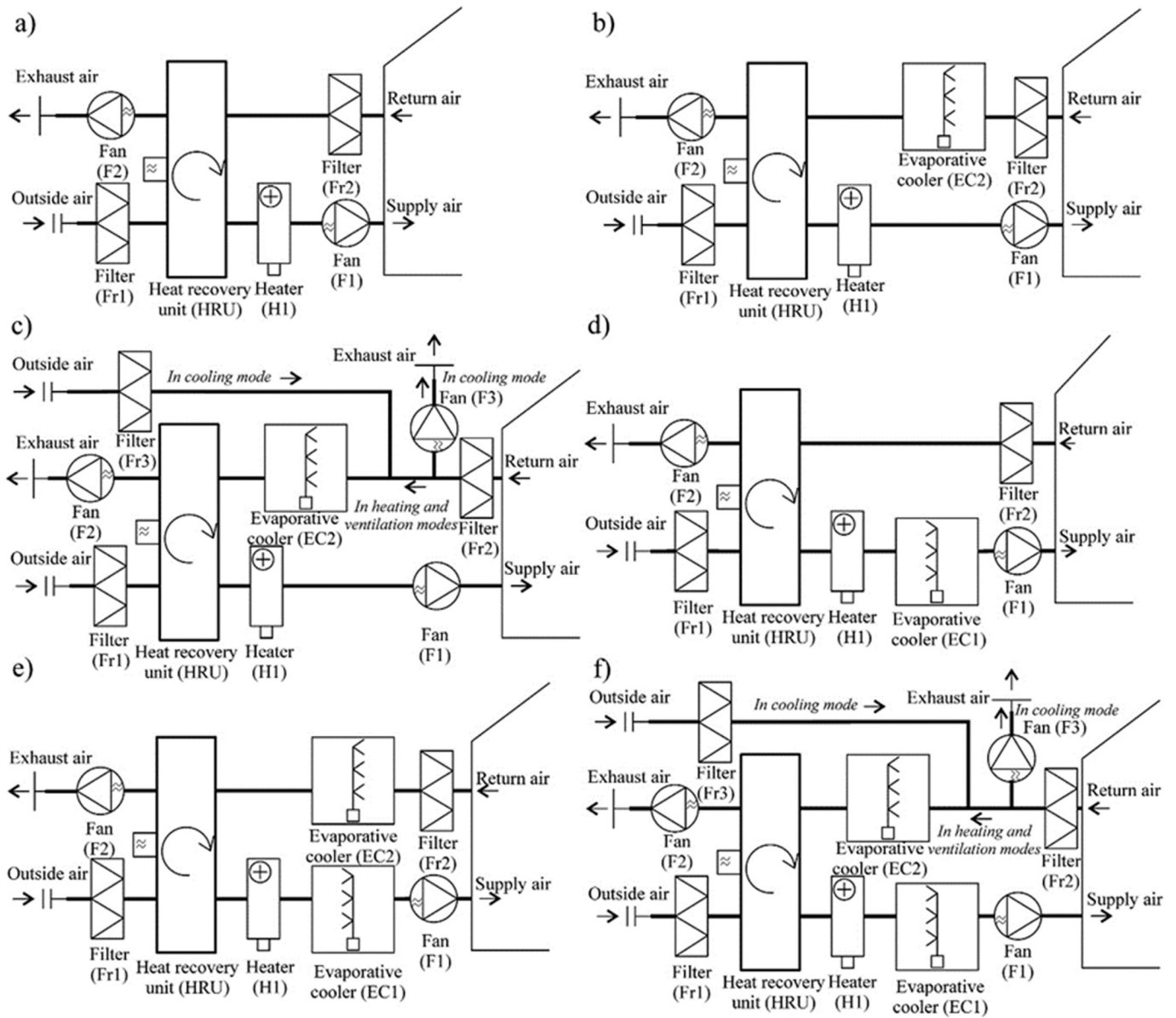


Fig. 5. Illustration of the investigated systems a) no adiabatic humidification, b) IEC, c) IEC using outside air, d) DEC, e) DEC + IEC, f) DEC + IEC using outside air [74]. Reprinted with permission from Elsevier.

The proposed system employs an ultrasonic atomizer to produce water mist (1 to 5 μm). Humidification caused by ultrasonic atomization to saturate the indoor exhaust air. The indoor exhaust air is then cooled down to its T_{wb} by the evaporation of fine mists. Consequently, sensible heat transfer occurs and total heat recovery is realized due to the condensation of the outdoor supply air moisture. Comparatively enhanced cooling effect caused by the ultrasonic atomizing (ultrafine mists) is due to increased area of water mists (for evaporation) and reduced thermal resistance between the supply and exhaust air streams. Besides, there is no contaminant transfer between exhaust and supply air. This is because no sorption or mass permeation, or carry-over occurs during the heat exchange. For hot and humid environment, the design can attain a 71% heat recovery efficiency while the moisture condensation from the supply air can recover almost 50% of the enthalpy.

3.4. IEC integrated with inverted Brayton cycle

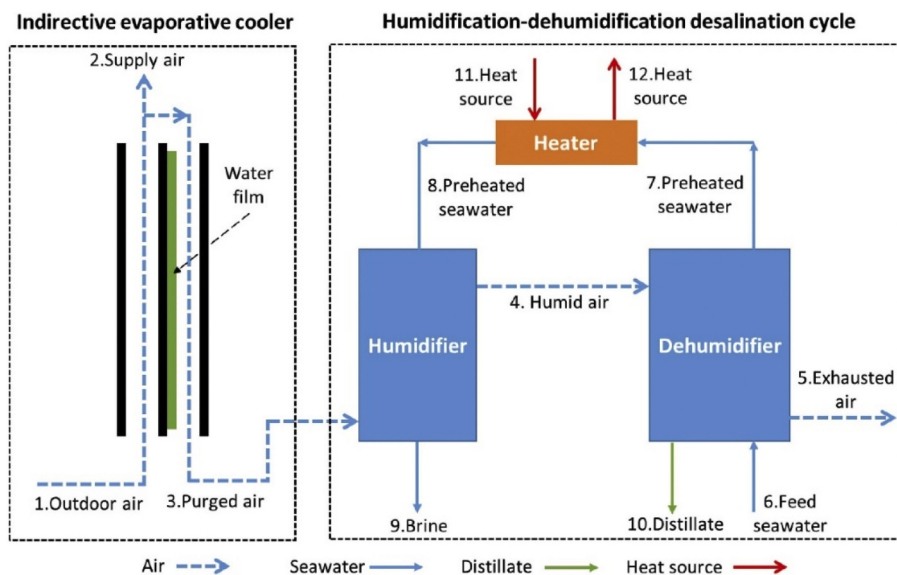
Particularly, the waste heat can be effectively recovered by the inverted Brayton cycle (IBC), even at a low source temperature.

However, this incurs rather low thermal cycle efficiency. To improve the performance, an inverted Brayton cycle is integrated with a counter flow IEC as depicted in Fig. 10 [76]. This system introduces the pre-conditioned working fluid to the compressor inlet. The proposed system showed up to 45% improvement in the specific work output regardless of air inlet condition and turbine inlet temperature. Besides, very high thermal efficiency was obtained when the heat source temperature is less than 85 $^{\circ}\text{C}$, and the thermal efficiency is inversely proportional to the humidity of working air entering the cycle. Furthermore, the IBC was found to be more efficient by incorporating with IEC as compared to the air-cooling and recuperator.

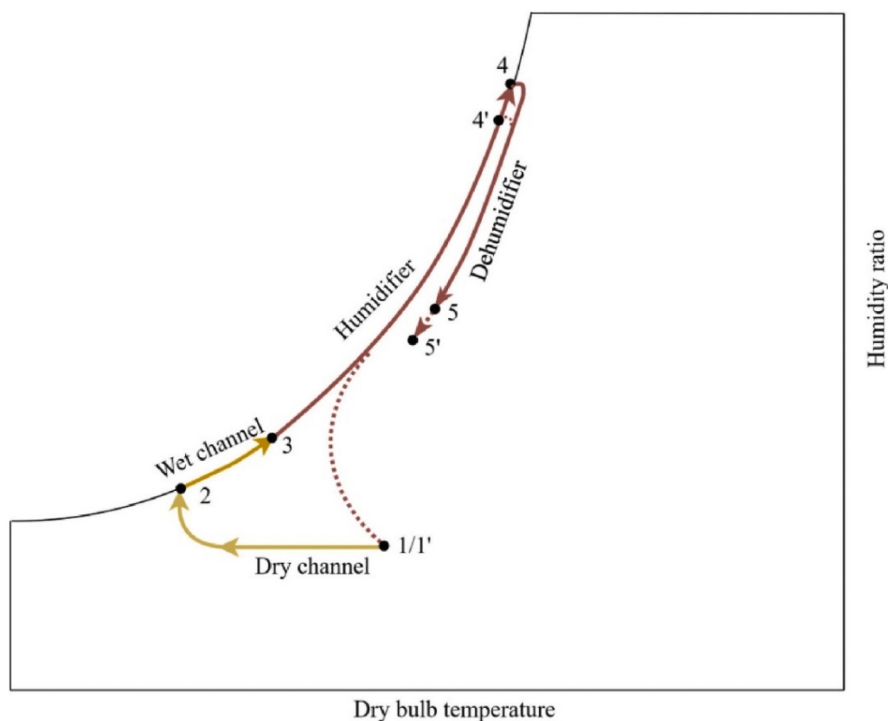
3.5. IEC integrated with a desiccant wheel

An efficient and economical hybrid system consisting desiccant wheel integrated with IEC was proposed as an alternative to the conventional (direct expansion) systems in order to achieve comfort conditions in the buildings with elevated latent loads [53].

Their numerical analysis was first validated from experiments and



(a)



(b)

Fig. 6. (a) Schematic representation of the IEC integrated humidification dehumidification (HDH) cycle, (b) Psychrometric representation of proposed IEC-HDH (1–2–3–4–5) and a basic HDH cycle (1'–4'–5') [63]. Reprinted with permission from Elsevier.

further extended to analyze the seasonal COP and energy consumption subject to various climate zones. As clearly seen in Fig. 11, it was found that for all climate zones, the DW-IEC was able to achieve 46.8% energy savings, far more than the conventional system, and higher energy savings lead to a higher seasonal COPs for the new system.

3.6. IEC integrated with DEC-IEC (direct evaporative cooler)

The performance of a multistage DEC-IEC with a heat pipe is evaluated with respect to water usage, output air humidity, and saturation efficiency. Fikri et al. [78] employs heat pipes in the first (to pre-cool)

and third stages (for indirect cooling), and their schematics of these two heat pipe modules are presented in Fig. 12.

The system is used to assess the system performance for inlet temperatures ranging from 36 to 45 °C and airflow rates of 0.4 to 1.4 m/s. From their experiments, it was reported that the two stages design (first and second) can alleviate the saturation efficiency although the RH of the outlet air and the water consumption are increased. The maximum reduction in temperature was achieved during the first stage when evaporation takes place. It was also observed that three-stage design yield a minor reduction in RH and temperature.

Optimal geometric and operational parameters for evaporative

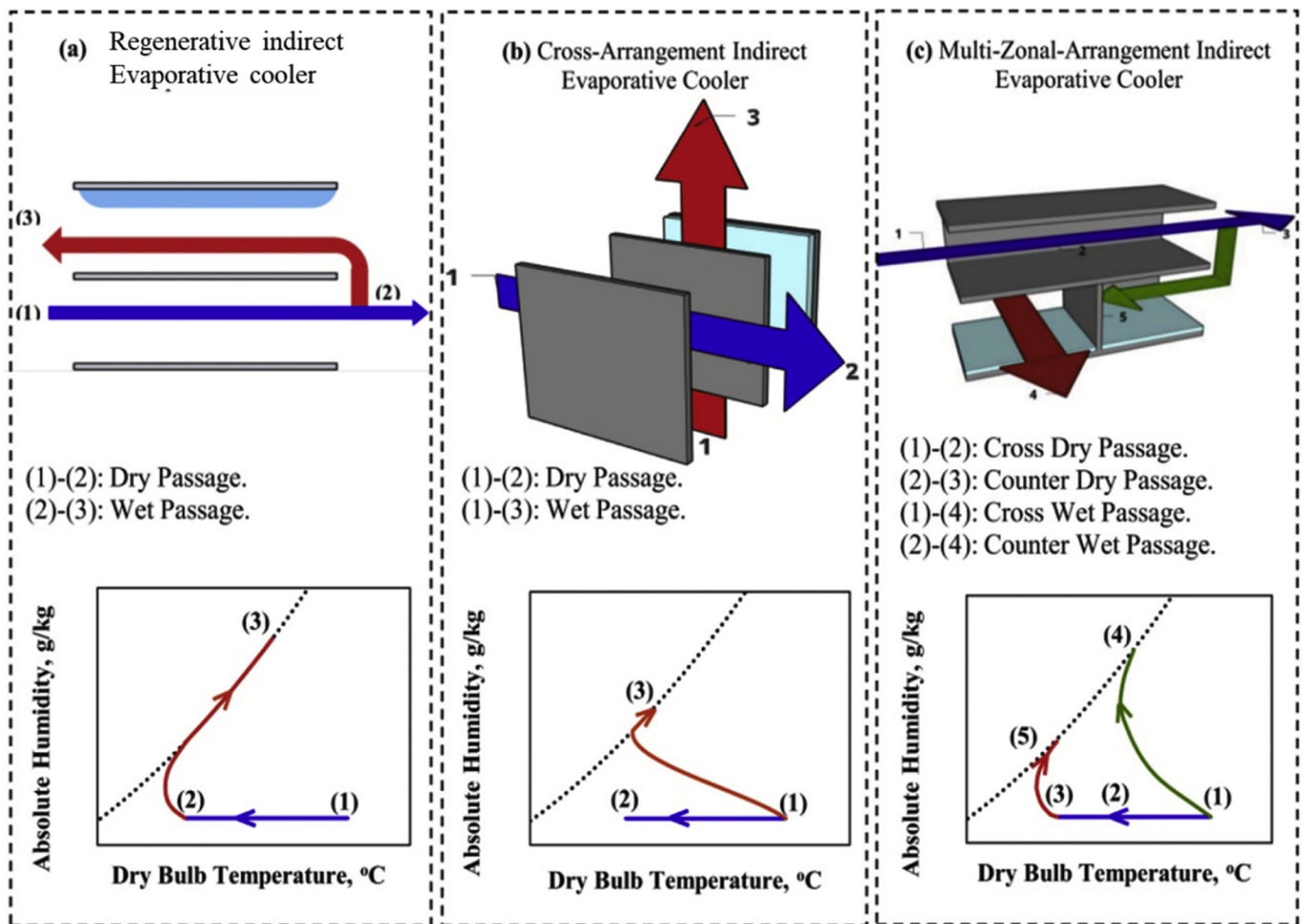


Fig. 7. Schematic and psychrometric diagrams of (a) counter-arrangement IEC, (b) cross-arrangement IEC, and (c) multi-zonal-arrangement IEC [66]. Reprinted with permission from Elsevier.

systems are achieved by a finite difference method (FDM) [56]. Among their investigated evaporative systems, cross-flow IEC and co-current DEC demonstrated the highest efficiencies of 40% and 73%, respectively. Hence, these two systems are further combined as shown in Fig. 13 to meet the cooling demands in various climates. With a high outdoor temperature of 40 °C, the lowest temperatures in primary channel for IEC and DEC have been achieved by air flow velocity of 0.25 m/s with the amounts of 34 °C and 27 °C, respectively.

3.7. IEC as a pre-cooler and pre-dehumidifier

In hot and humid regions, an indirect evaporative cooler (IEC) acting as a pre-cooler and pre-dehumidifier could be utilized as an effective means by apprehending the cooling potential of exhaust air coming from the air-conditioned indoor environment [80] (see Fig. 14). The retaining condensate in the primary channels has a serious influence on thermal performance of IEC. Moreover, the inlet primary-air conditions (temperature and RH) have a profound impact on the heat transfer (condensation) performance of the system. The experimental findings also suggest that dropwise condensation should be promoted to improve the performance of air conditioners.

Another hybrid air-conditioner integrated with IEC (pre-cooler and pre-dehumidifier) is proposed [54]. A schematic and psychrometric representation of the proposed system is presented in Fig. 15. The proposed system employs the exhaust air from the room to pre-condition the intake ambient air via IEC. Performance of the Pre-cooler is theoretically evaluated in different climate zones.

The psychrometric chart indicates the IEC can dehumidify and pre-cool the ambient air (see Fig. 15). Besides, the IEC as a pre-cooler shows the noticeable (57%) energy saving potential. For instance, the proposed system can fulfil up to 57% of the fresh-air cooling load. In addition, the proposed system can be easily integrated with the new and existing air conditioning systems. However, it requires additional space to accommodate the IEC into the system, hence designing a more compact system in the future is imperative in order to commercialize this technology.

3.8. IEC with a novel air distributor for precise temperature control in multiple compartments

Although the domestic refrigerators with multi-compartment indirect-coolers (MIRs) contain the benefit of having different temperatures in multiple compartments (freezing, refrigerating, and variable temperature compartments), precise temperature control of each compartment is actually quite difficult. This is because the MIRs fail in delivering the independent cooling capacity to each compartment. To tackle this problem, a new air distributor is installed in a MIR system and the position of air-supply dampers in the air distributor is changed [81].

The novel air distributor is shown in Fig. 16. The novel air distributor achieves different cooling capacities for each compartment by adding an FC damper, which in turn changes the structure and the airflow resistance of the duct. A comparison between the novel and conventional air distributors confirms the effectiveness and precise temperature control of the proposed system.

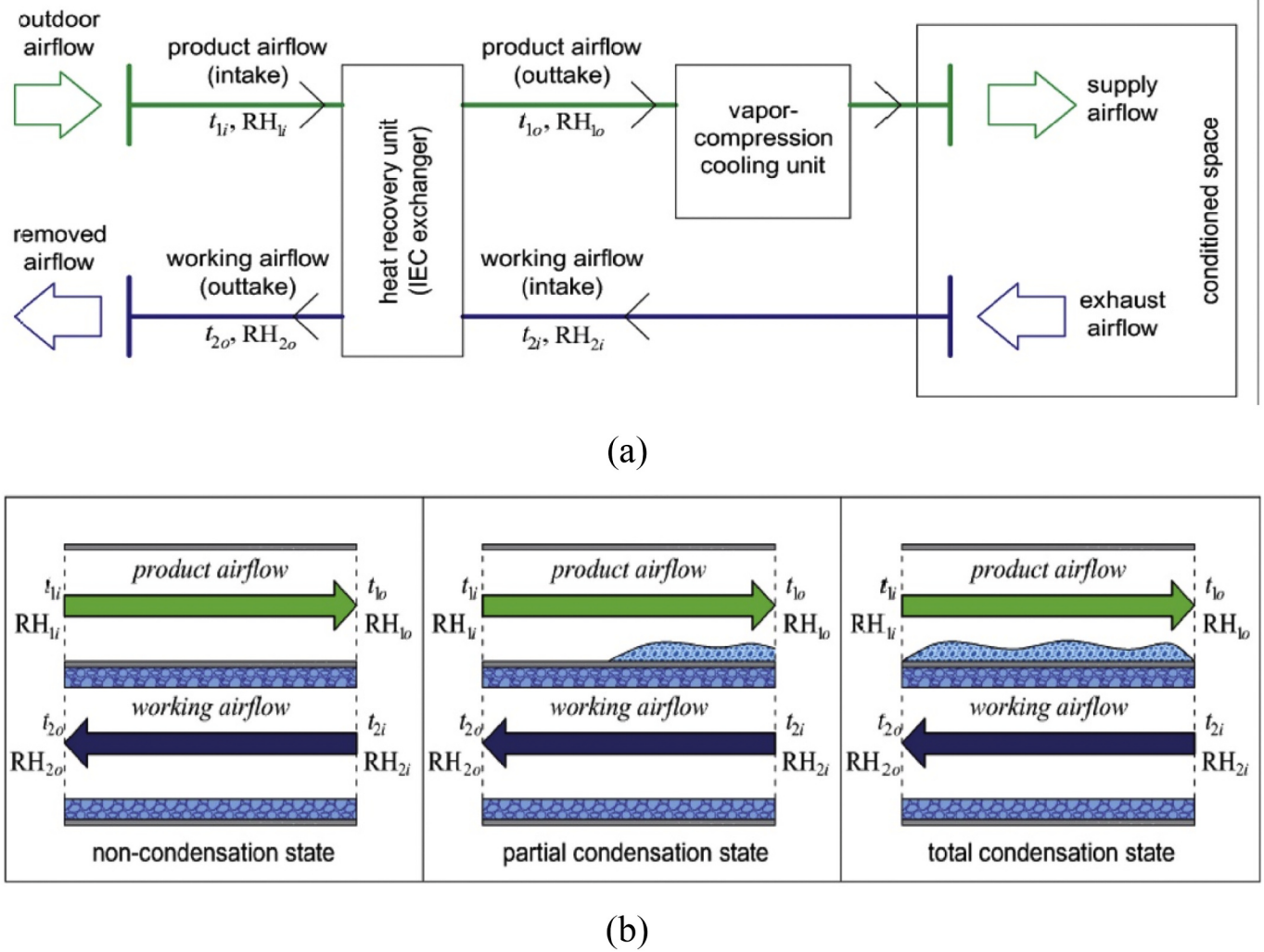


Fig. 8. Schematic of (a) IEC-HMX, (b) possible condensing states in product air channel [50]. Reprinted with permission from Elsevier.

3.9. Efficiency enhancement of IEC via wettability control

The wettability in wet channels plays an important role in cooling performance of an indirect evaporative cooler (IEC). One of the effective way to improve the performance of the IECs is via wettability control of the wet channels. One of the methods for wettability improvement is to employ porous ceramic tube as seen in Fig. 17 [79]. The porous structure features water absorption and hydrophilicity that reduce the formation of water droplet or water film, thereby improving the wet bulb efficiency of the cooling unit. Different geometric (wall thickness, tube length and spacing) and operating parameters (T_{wb} depression and working air volume ratio) of porous IEC are studied. The optimal tube spacing is 40 mm, and the length of the tube under 1.5 m has a remarkable influence on the IEC performance. To maintain the optimal performance, the working air and product air velocities should be under 4.0 m/s and 3.4 m/s, respectively with a working air volume ratio as 0.9.

A deterioration in cooling efficiency of IEC in practical circumstances is associated with the poor wettability of the wet channels. Water spray strategies and the nozzle types greatly affect the wetting conditions of the wet channels. An investigation has been conducted to homogenize the water film distribution inside the IECs via introduction of some novel materials [77]. These materials optimize the nozzle configurations and improve the diffusion. For this purpose, a quantitative investigation of various spray nozzles (spiral, conical, square, sector, and target) has been performed and some optimal nozzle designs are illustrated in

Fig. 18.

From the findings, the spiral type nozzles are affirmed to be the optimal design for IEC systems. This is because it offers better uniformity, prominent coverage ratio, and acceptable sprayed volume distribution. Although target impact nozzles are good enough in terms of the coverage ratio and uniformity, their sprayed water volume distribution is limited in many areas.

3.10. Efficiency enhancement of IEC via condensation effect

In the IECs, condensation occurs when the wall temperature falls below the dew point temperature of the air. Consequently, the amount of heat exchange is increased, and the wet bulb and total efficiencies are reduced [87]. High dew-point temperatures of primary air streams in humid and hot areas cause condensation. A study was reported to visually investigate a cross flow IEC with condensation under different ambient conditions [70]. It was concluded that condensation caused an improvement in heat transfer, outlet temperature of primary air, and water consumption. However, the wet bulb effectiveness was lowered. Moreover, the thick water film results in considerable amount of thermal resistance of condensate and pressure drop to the airflow. A study shows that the condensation process can substantially reduce the thermal load of fresh air [88]. Even though the condensation may deteriorate the sensible heat exchange, the latent heat transfer can reach around 4.6 kW and up to 40% moisture-contents in the fresh air can be eliminated upon

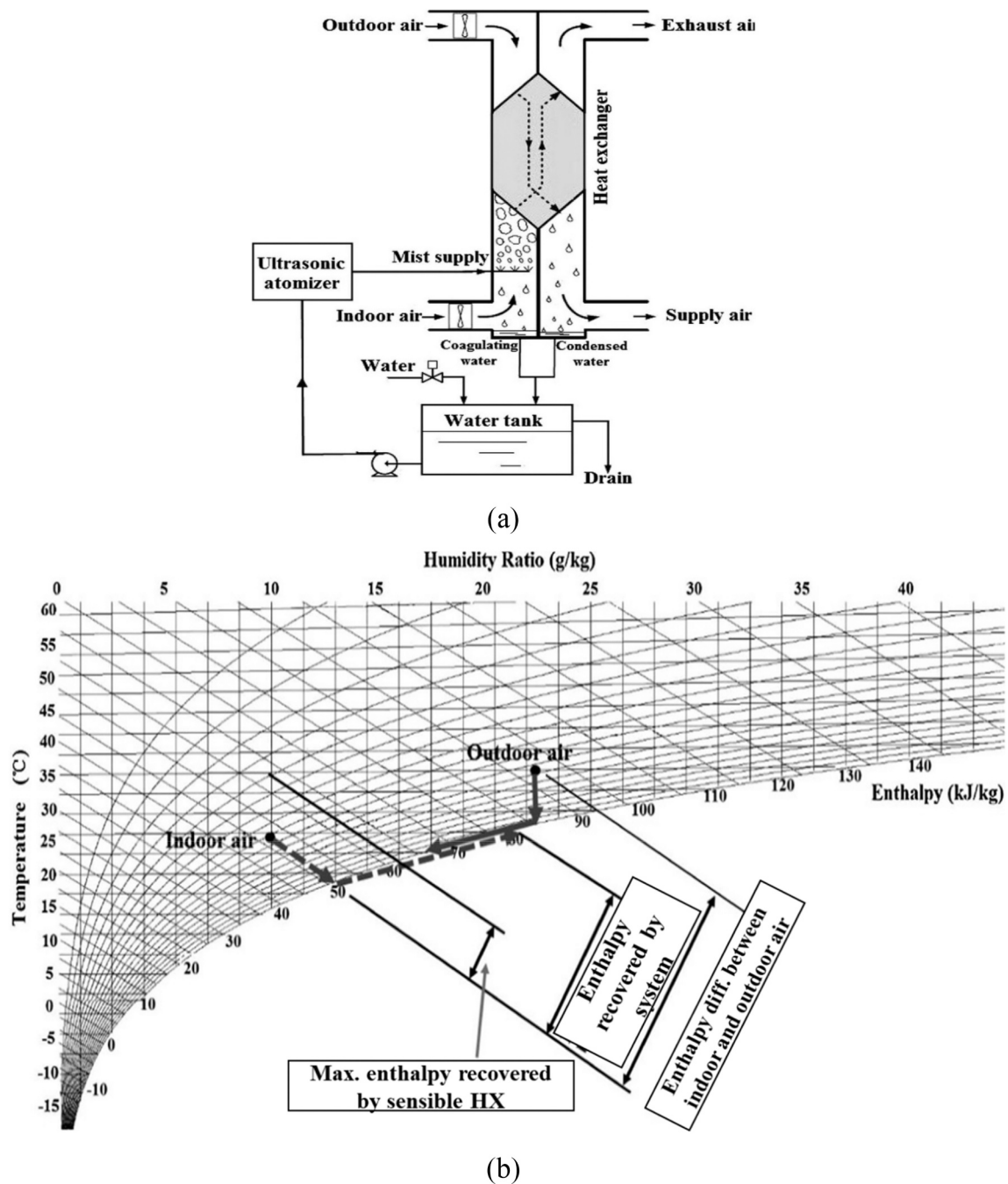


Fig. 9. The proposed total heat recovery system (a) principle, (b) psychrometric process [71]. Reprinted with permission from Elsevier.

full condensation.

It is extremely important to alleviate the influence of condensate and to reduce the condensation area ratio particularly in hot and humid environments. This is because the condensation occurs definitely on the primary channel's walls (primary channel) when IEC is integrated with air conditioners for supplying the fresh cool air. To tackle this problem, a 2D mathematical model has been developed for a plate crossflow IEC taking into account the condensation ratio (see Fig. 19). Fig. 19 shows that primary air flows horizontally while the secondary air flows in the vertical direction. The water droplets coming (opposite to the secondary air) from the nozzle are assumed uniformly distributed on the secondary side. Once the T_{dp} (dew point) crosses the wall temperature, condensation starts. In this study [60], MATLAB and finite difference method have been used to analyze various states of condensation such as total

condensation, partial condensation, and no condensation. Upon validation with the experimental results, the model showed a deviation around 8.6%. It was concluded that dehumidification rate, total and latent heat transfer are directly proportional to the condensation ratio while the wet bulb efficiency and sensible heat transfer are inversely correlated with the condensation ratio. A new evaluation index namely the enthalpy index was introduced and used to plate counter flow and cross flow IECs. With the help of the new index, the heat transfer capacity of the IECs can be evaluated. Besides, it can be employed for selecting the equipment design, optimizing the performance, and performing the thermal calculations for an IEC. A further investigation was carried out to optimize the fruits and vegetables storage environment (temperature and RH) by integrating the evaporative cooler with indirect air cooling (EC + IAC) system. The measurement values of 28 days

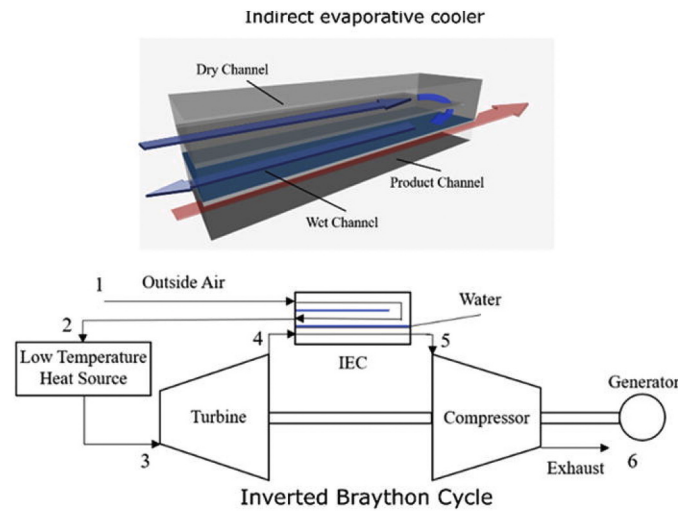


Fig. 10. A hybrid IEC-IBC (inverted Brayton cycle) system [76]. Reprinted with permission from Elsevier.

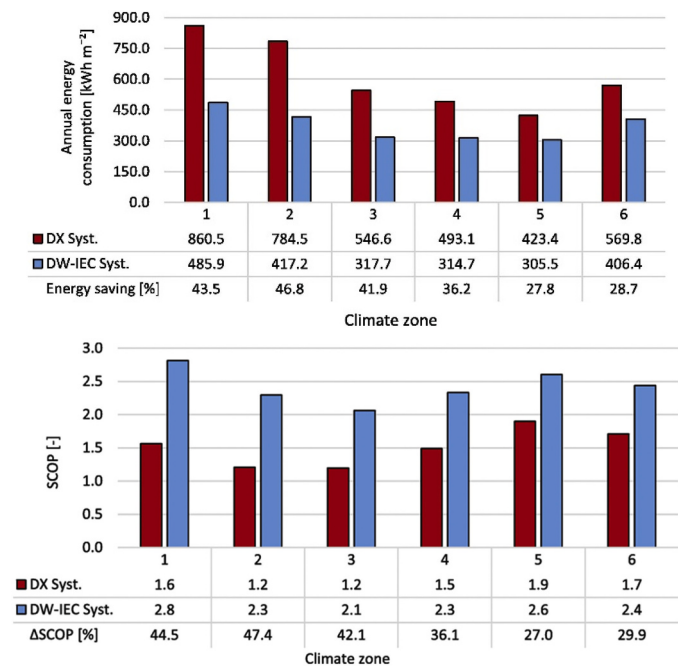


Fig. 11. Comparison of DX and proposed DW-IEC systems in terms of (a) annual energy consumption, (b) seasonal COP values [53]. Reprinted with permission from Elsevier.

proved the effectiveness of the EC + IAC system over ambient conditions. The experimental findings (low temperature and high RH of the new system compared to the ambient) affirm the potential of EC + IAC system as an energy saving approach for storage applications in humid, sub-humid, and hot climates. Pandelidis et al. [89] reported that the counter-flow arrangement has higher latent and sensible cooling potential compared to the cross-flow unit. However, the cross-flow exchanger has lower investment cost. In an investigation, a 2-D analytical model of cross-flow IEC accounting for the condensation from fresh air was developed [90]. It was shown that the condensation has more probability of occurrence close to the outlet of fresh air and inlet of exhaust air. It was also reported that under full condensation, up to 3.9 kW of latent energy could be reached while almost 30% moisture from the fresh air could be removed. Another 2-D mathematical heat and

mass transfer investigation [60] of a plate-type cross-flow IEC considering condensation was developed. It was revealed that the term “condensation area ratio” has positive correlation with latent heat-transfer, dehumidification rate, and total heat-transfer; it has correlation with wet-bulb efficiency and sensible heat-transfer. A numerical analysis of a M-Cycle cross flow below dew point IEC in humid conditions considering the condensation was performed by Pandelidis et al. [91]. They have shown that their proposed cooler demonstrates superior performance than a typical cross flow M-Cycle evaporative cooler is shown in Fig. 20.

4. Cross-flow dew-point indirect evaporative cooling (C-D-IEC) and its integration with other cycles

IEC is one of the most novel methods to cool the primary air near the dew point temperature of inlet air [92]. C-D-IEC is sometimes called M-Cycle IEC. This was developed by Maisotsenko and is known as M-cycle indirect evaporative cooling system. In dew point indirect evaporative cooling (D-IEC), the process air temperature is lowered below its wet bulb temperature (T_{wb}) without any moisture addition till the dew point temperature is reached. There are two different dry channels for process and working air. Primary air flows in one dedicated dry channel and exchanges sensible heat with wet channel. Primary air comes out with temperature near dew point temperature of the inlet ambient air. Depending upon the design, the working air flows in other dry channel for precooling and then was diverted to wet channel through single or multiple passages to facilitate heat transfer with primary air. Here moisture level of secondary air is increased and eventually the secondary air comes out at the outlet 3 becomes saturated. The flow process on psychrometric chart is clearly explained. The temperature near the outlet of the primary air is close to dew point and that is why it is also called dew point indirect evaporative cooling system.

The effectiveness of the M cycle evaporative cooling exceeds that of conventional indirect evaporating cooling system by about 10–30% but requires much complex construction to yield the flow pattern. Due to enhanced cooling effectiveness, it has been the major interest of researcher recently to replace the conventional mechanical vapor compression air conditioning system [33,93]. Due to higher effectiveness and cooling capacities, it has been investigated in various fields like heat recovery systems, turbines, and the like [94,95].

An investigation was carried out to evaluate the performance of a solid desiccant dehumidifier integrated with M-Cycle based cross flow heat and mass exchanger (MC-DAC) [67]. Desiccant and heat recovery wheels were coupled with C-D-IEC system. Various inlet air variables such as humidity ratio, regeneration temperature, and ambient air temperature were employed as performance parameters to make a comparison with the conventional DAC (desiccant air conditioning) systems. Conventional and proposed DAC systems are compared as shown in Fig. 21. MC-DAC system showed up to 60–65% higher COP_{th} than conventional DAC (desiccant air cycle) at low regeneration temperatures under same supply air scenarios. An added benefit of the proposed system is no moisture addition in supply air. For subtropical climates, a comfort condition was achieved at a low regeneration temperature (70 °C). However, for hot and humid climatic conditions, the proposed system may require higher regeneration temperatures than that of a conventional DAC requires.

A certain amount of energy (air-conditioning of the buildings) can be saved by integrating the D-IEC with a conventional refrigeration system [58]. The proposed climate wizard system is a counter flow D-IEC, which contains alternating wet and dry channels, as displayed in Fig. 22. State 1 shows that the moist air is entering the system and then moving along the dry-channels to be cooled till state 2. Subsequently, the cooled air recirculates and moves along the wet-channels (evaporation produces cooling), and then discharged in state 3 (see Fig. 22).

Two M-cycle IEC systems are investigated i.e. (a) M-cycle as a pre-cooler of the external air integrated with a refrigeration system and

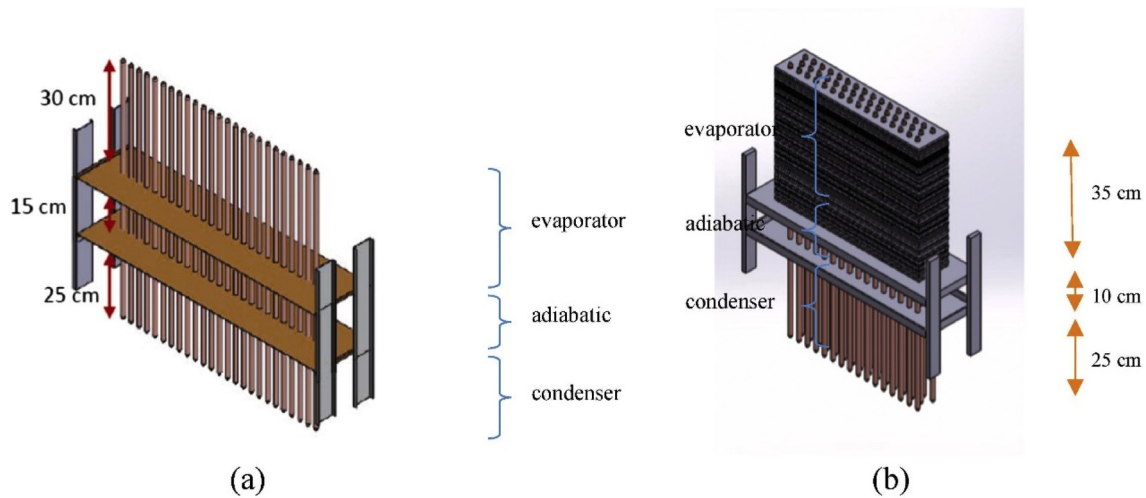


Fig. 12. Representation of heat pipe modules (a) first and (b) second [78]. Reprinted with permission from Elsevier.

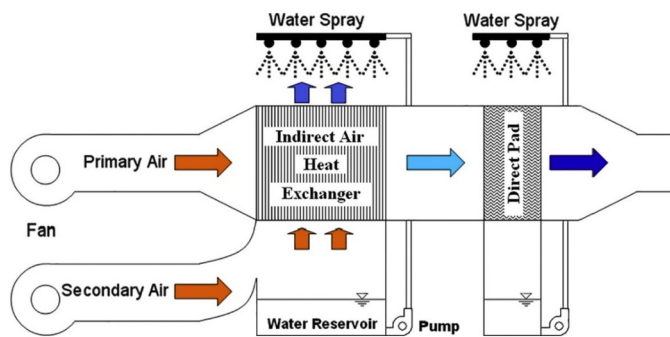


Fig. 13. A hybrid indirect/direct evaporative cooling system [56].

(b) M-cycle as a cooler of recirculated air integrated with a refrigeration system with heat recovery. From the evaluation, the second system was found to be more superior as it could yield a total 38% electric energy saving. The reduction in heating energy was caused by avoiding the reheat after dehumidification, without sacrificing the thermal comfort. Significant amount of efforts has been made to investigate and optimize the cooling performance of D-IEC systems. One of such study analyzes different kinds of purge configurations (heat and mass exchangers) for D-IEC as depicted in Fig. 23 [49].

A multi-object optimization was carried out to find the optimal designs for two popular configurations of the D-IEC, including cross-flow and counter-flow regenerative based configurations subject to influence regaining three performance parameters such as annual water consumption, annual average of COP, and life-cycle cost. These optimal designs were suggested in small residential buildings. Geometric and operational features of the coolers were considered as the design parameters. Subsequently, the optimal counter-flow regenerative configuration was tested under different climates. In summary, the counter-flow regenerative configuration is the best choice for hot and arid regions while the cross-flow configuration was a better alternative for other climates. The optimal configurations demonstrated some improvements of 86.4, 64.4, and 1039.0% in the annual water consumption, life-cycle cost, and the annual average of the COP, respectively. An investigation was carried out for economical and thermal comfort evaluation of a two-stage direct-indirect evaporative cooler in greenhouse applications [69].

The proposed system comprises a cellulose pad (DEC as a first stage) along with a counter-flow regenerative M-cycle IEC (CoFRMC as a second stage) module as demonstrated in Fig. 24. The outside air is driven

by a blower to pass through DEC and is cooled isenthalpically first before it is further directed to the CoFRMC, and eventually to the conditioning space. From the Fig. 24 (b), it can be seen that the combined DEC-IEC has the ability to deliver a lower temperature than that of the individual modules. Therefore, this system can be a potential solution to provide thermal comfort in those areas where the DEC or IEC systems are unable to do so separately. Hybrid systems equipped with effective control can maintain the desired humidity and temperature within the greenhouse, particularly in hot climates. It was found that water consumption ratio is highly dependent on the pad's thickness. Thinner pads are suggested for both single stage and two stage evaporators.

A highly efficient C-D-IEC with optimal water and airflow scheme was reported, which showed an improvement in the COP and wet bulb efficiency up to 34.6% and 29.3%, respectively, than that of the commercial C-D-IEC having the same capacity [51]. Size and capacity of the cooler were scaled and optimized by the numerical simulations. The numerical findings indicate that the structure of the cooler has a strong influence on the cooling rate. Furthermore, C-D-IEC with corrugated plates exhibits 10% higher cooling efficiency when compared to the cooler with flat plates. Moreover, the cooling efficiency of D-IEC with actual flow arrangement is 62%–67% higher as compared to the cooler with ideal flow scheme. The higher efficiency of ideal flow arrangement is due to the increased channel and air entrance lengths and reduced channel gap and width up to a certain limit. A numerical and experimental study presents a novel, highly efficient counter flow C-D-IEC (dew point cooler) integrated with an unguided and corrugated HMX [59]. They developed a full-scale building energy model to investigate the effects of climates such as subtropical, Mediterranean, hot continental, and hot desert climates. The model shows close prediction against the experimental data, and can be regarded as an effective and efficient approach to optimize evaporative cooling systems for a wide range of operating conditions and buildings.

A comparative numerical investigation of two C-D-IEC based cross flow HMXs (heat and mass exchangers) namely regenerative (R-HMX) and conventional is carried out [57]. Schematics and airflow schemes in the channels for both HMXs are provided in Fig. 25. The comparatively higher efficiency of the R-HMX is because it utilizes the pre-cooled air (unlike conventional HMX). For stand-alone HMXs, the R-HMX performed much better than conventional HMX at low supply airflow rates. However, in multistage evaporators, for high supply airflow rates, the conventional HMX is more beneficial during the first stage (as a pre-cooler) whereas the R-HMX is suitable during the second stage (as a re-cooler).

The findings of a study suggest that the solar desiccant coolers integrated with Maisotsenko-Cycle demonstrated the superior

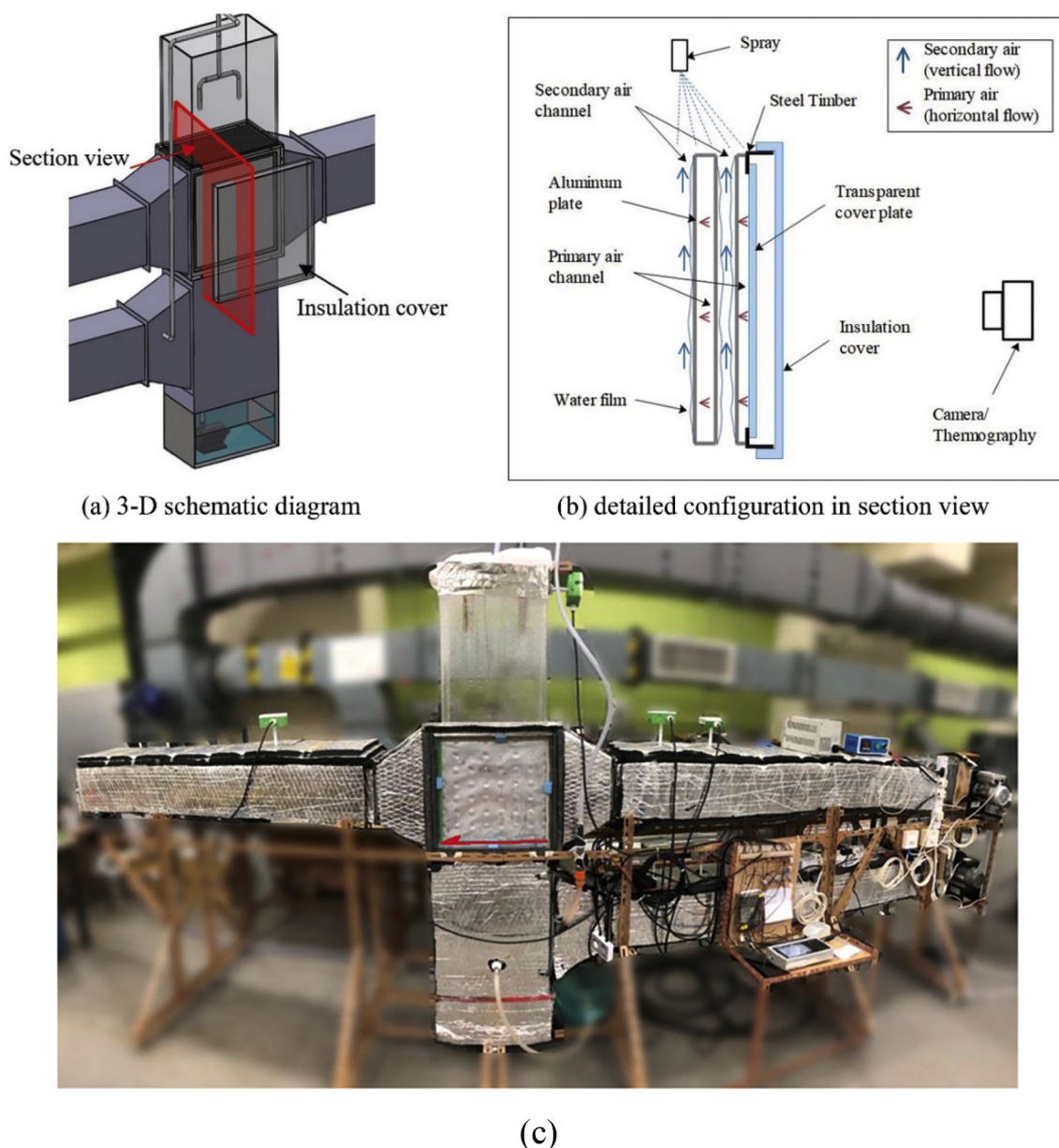


Fig. 14. (a, b) Outer primary air channel in IEC and (c) IEC test rig [80]. Reprinted with permission from Elsevier.

performance over those combined with the evaporative coolers [96]. Pandelidis et al. [97] developed a novel multistage DAC (desiccant air conditioner) for the moderate climatic conditions. Their proposed multistage cooling originates from a M-Cycle, regenerative HMXs (heat and mass exchangers) integrated with a desiccant wheel. They found that the proposed multistage cooler was able to achieve a thermal COP of 4, which makes it suitable for moderate climate applications. Shahzad et al. [67] designed a MC-DAC (M-Cycle evaporative cooler integrated with a desiccant system) and found that their designed system is able to perform better at low regeneration temperature of 70 °C compared to the DAC in subtropical climates. In another study, Pandelidis et al. [98] designed a hybrid air conditioner that consists a dew-point IEC. While evaluating in temperate climate, it was found that the proposed cooler operates as regenerative cooler when outdoor air is less humid than indoor air. It can become a counter-flow heat recovery system when indoor air is more less humid than outdoor. Also, it is capable to function as a combination of two arrangements. A hybrid RC/DX (regenerative evaporative cooler integrated with a direct expansion system) was modelled in Beijing, China [99]. It was found that almost 32

to 48% of energy could be saved by the REC/DX system whereas 26 to 42% of the energy via classic IEC/DX system, compared to the conventional direct expansion system for a cooling season.

5. Regenerative indirect evaporative cooling (R-IEC) and its integration with other cycles

Regenerative IEC is a form of dew-point IEC, with counter-flow arrangement, where both air streams are initially driven through the dry channel followed by a separation at its final part (two portions of the air are delivered to the working channel and the occupants). The regenerative evaporative cooling system (R-D-IEC) is an improved version of indirect evaporative cooling system, a portion of the product air is extracted at the outlet and is directed towards wet channel as the working air [20]. In this case, working air is already cooled, so the wet bulb temperature is lower than that of regular outside working air. As a result, the product air is cooled below the wet bulb temperature and close to the dew point temperature of ambient inlet air. Working principle and corresponding psychrometric chart are depicted in Fig. 26.

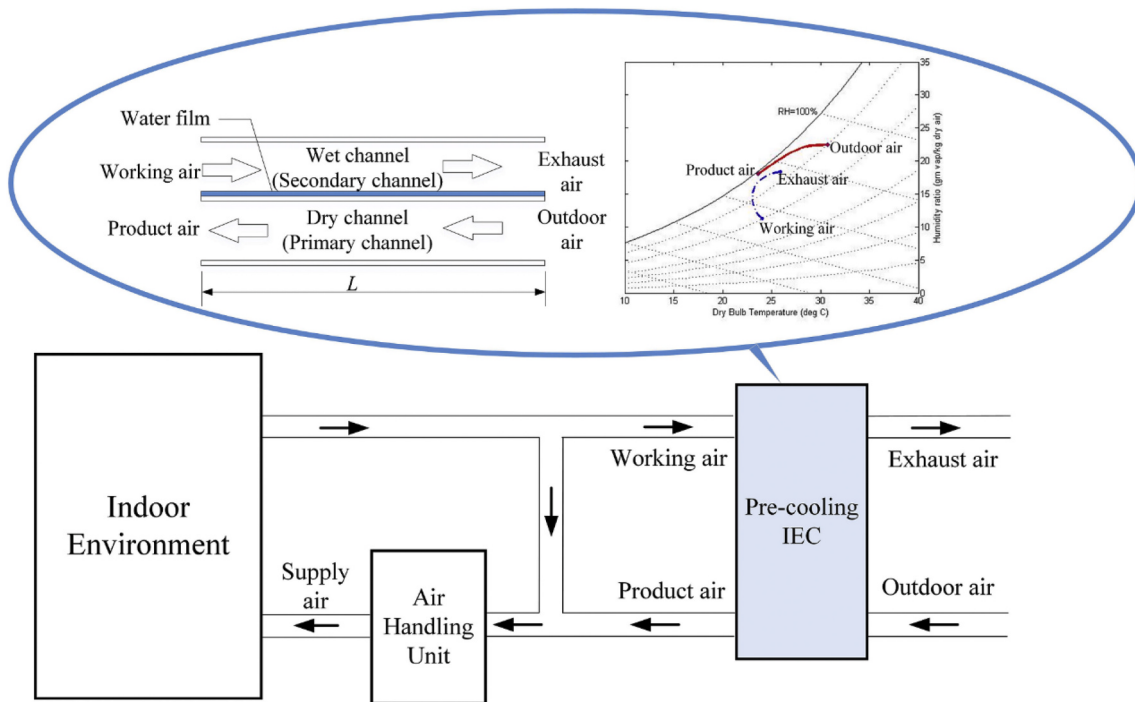


Fig. 15. A schematic and psychrometric representation of the proposed system [54].

The warm primary outside air (1) enters dry channel and exchange sensible heat with wet channel and reach outlet (2) with a lower temperature. At point (2), a portion of primary air is extracted and diverted in wet channel where it is humidified and exchanges latent heat of vaporization and finally leaves the wet channel at point 3. Here in process 1–2, the primary air has constant moisture content and finely the dry bulb temperature achieved is lower than the wet bulb temperature of inlet primary air. However, due to extraction effect the flow rate of primary air is lower than that in conventional indirect evaporative cooler.

A regenerative evaporative cooler (REC) is an environment-friendly, sustainable, and efficient cooling option [100]. For an efficient R-IEC system, proper configuration should be chosen in terms of primary and secondary air, and flow directions of water. A study investigates different configurations of a regenerative (i) parallel/counter flow evaporative cooler, (ii) regenerative cross-flow evaporative cooler is as presented in Fig. 27 [48]. The operating and geometric parameters are analyzed for various configurations.

Within the configurations of REC as seen in Fig. 27, configuration A and H are best in terms of lower specific total cost and higher sustainability index. The investigation suggests that improved sustainability index and exergetic efficiency along with reduced CO₂ emission can be achieved by lowering the airflow rate, channel gap, and extraction ratio.

In another study, a novel regenerative evaporative cooler (R-D-IEC) unit was proposed [64]. In the proposed system, integrated porous ceramic tube and heat pipe replace the plate HXs (see Fig. 28). Under laboratory testing conditions, COP and cooling heat flux can reach up to 11.43 and 140 W/m², respectively. Moreover, the results reveal up to 14 °C reduction of supply air relative to ambient air could be achieved under certain environmental conditions.

An IEC depends on the ambient conditions. Better thermal comfort and stable indoor environment require a proper control scheme. However, very few studies have been reported for the control strategies in IEC. A recent study compares two control strategies for R-IEC systems namely a novel high-low control (H-L) and the conventional on-off control [55]. The on-off control mode keeps the fans running at constant speed or turning off in case of satisfactory indoor temperature

whereas the H-L control mode keeps the fans switching between high and low speeds instead of entirely being turned off. It is found that superior performance of H-L control mode prevails in terms of either thermal comfort, energy saving (11.3% higher than on-off control), or indoor air-quality. The H-L control scheme is more effective in transitional seasons with slight variations in indoor temperature, such as with smaller indoor temperature variation range, low switching frequencies of the speed of fan, and insurance of fresh air.

Regenerative (R-D-IEC) evaporative cooling is an advanced IEC technology that can provide the cooling below wet bulb temperature. It contains many configurations by manipulating the directions of airflow (primary and secondary) and water-flow. These configurations affect their performance distinctly. An attempt has been made to numerically investigate the performance in terms of their effectiveness, the COP, and the cooling capacity for all possible airflow (cross flow and parallel/counter flow) configurations having downward direction. Different geometries (gap of the dry and wet channels) and operating parameters (inlet humidity, temperature, flow rate, and extraction ratio) are examined. The results indicate that parallel/cross flow in wet channels are the best overall subject to their investigated conditions.

6. System configuration

To achieve high dew point, wet bulb effectiveness, and cooling capacity, several attempts have been made in taking into account the operating conditions and design configurations of the indirect evaporative cooling system. Major designs configurations are cross- and counter- flow evaporative cooler (see Fig. 29). Riangvilaikul and Kumar [32] performed experiments on counter-flow R-IEC at different operating conditions, and reported higher dew point effectiveness (wet bulb 0.58 to 0.84, dew point 0.92 to 1.14) when compared with previous data of cross-flow type. Bruno et al. [23] developed onsite experimental setup for counter-flow flat type regenerative evaporative cooler for residential and commercial applications. It was used as a pre-cooler of refrigeration air conditioner. Wet bulb effectiveness can reach 93–106% for commercial application and 18–129% for residential purpose. Moshari and Heidarinejad [101] numerically compared cross-flow and counter-flow

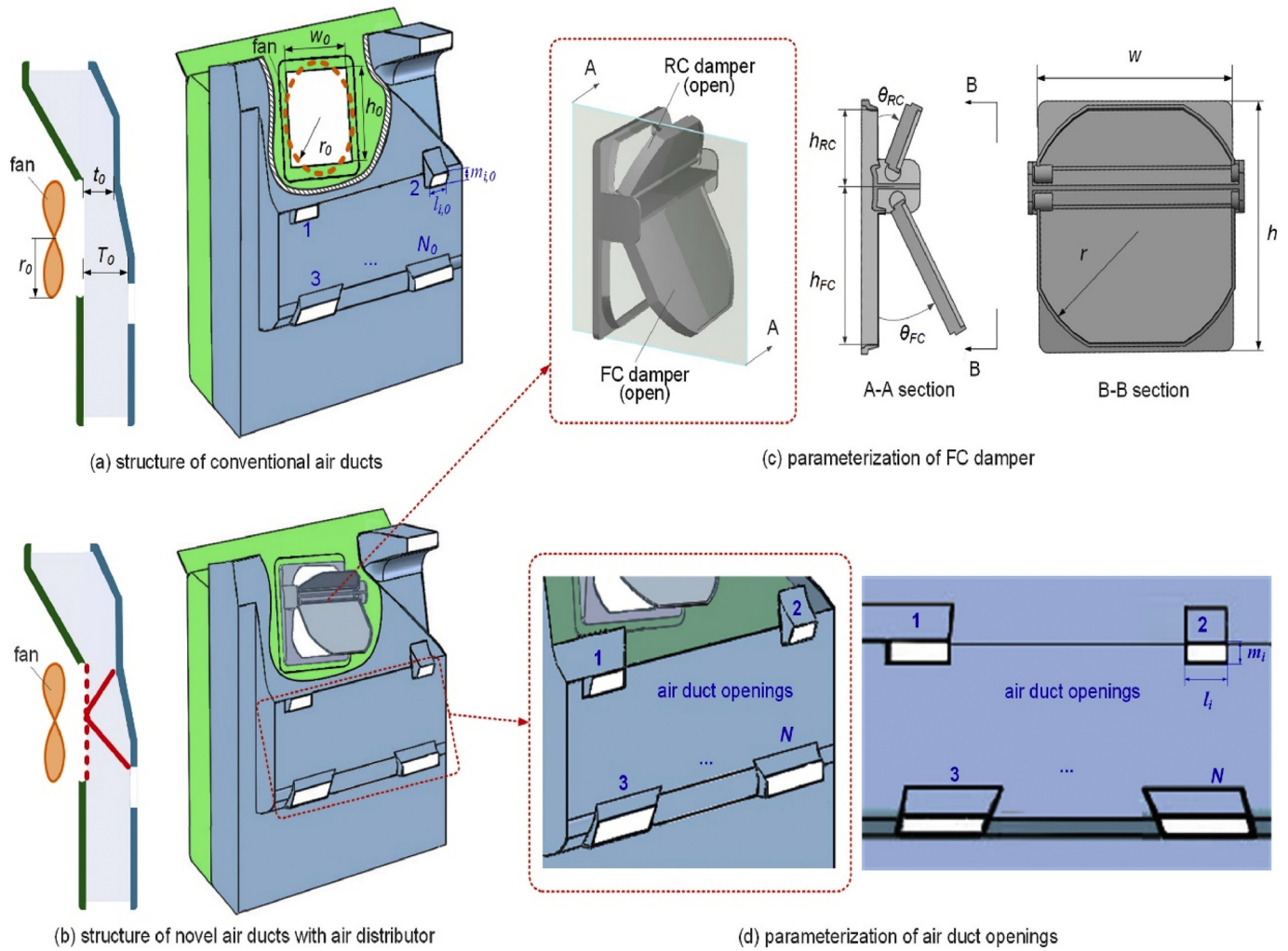
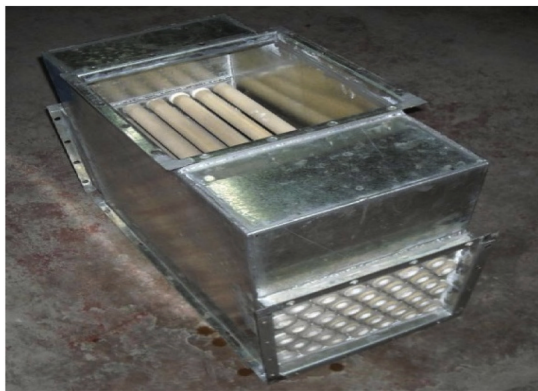
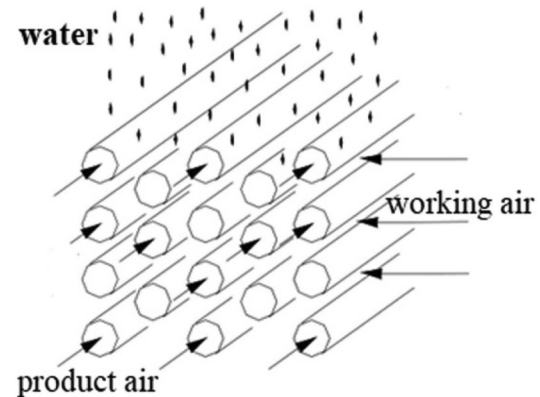


Fig. 16. Structure of conventional and novel air distributors [81]. Reprinted with permission from Elsevier.



(a)



(b)

Fig. 17. Porous ceramic tube type IEC (a) original photo and (b) schematic [79]. Reprinted with permission from Elsevier.

configurations of regenerative evaporative cooler and found that counter-flow R-IEC has higher cooling ability than cross-flow design. Recently, Zhao et al. [102] also performed a comparative study on cross-flow and counter-flow dew point evaporative coolers (D-IEC). Their results indicate that the counter-flow arrangement yields 15% higher dew point efficiency, 22.5% higher wet bulb efficiency and up to 20%

higher cooling capacity. However, the COP of cross-flow arrangement was 10% higher than that counter-flow arrangement. It can be concluded that counter-flow offers more cooling effectiveness as compared to cross-flow arrangement. Yet counter-flow arrangement also shows better system compactness. In essence, for higher cooling efficiency and compactness, the counter-flow configuration has greater

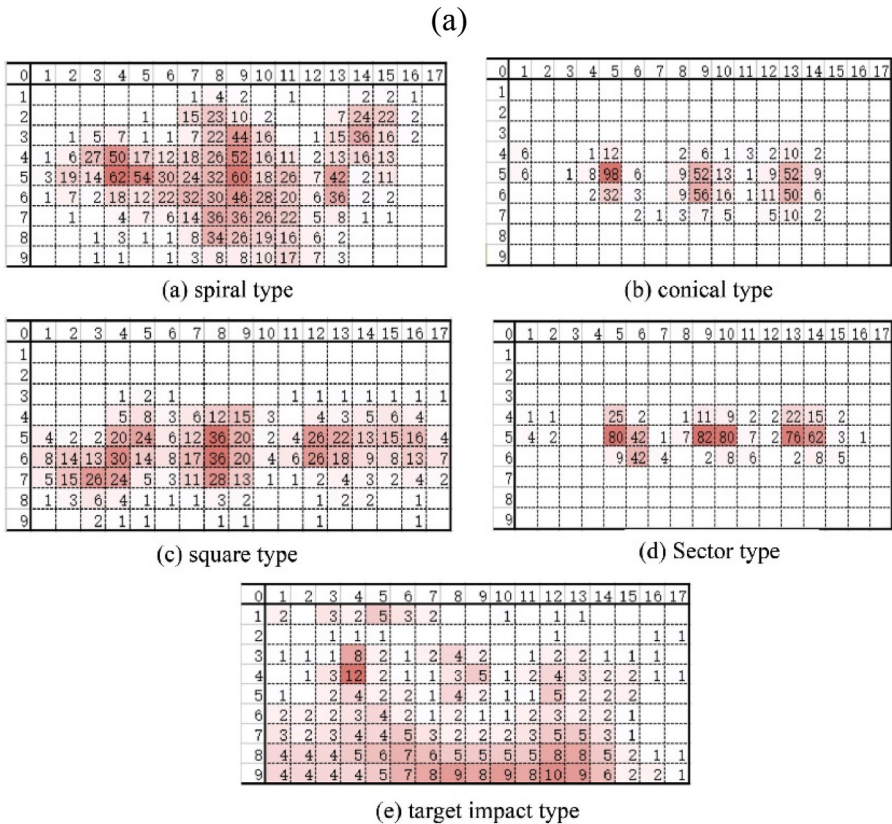
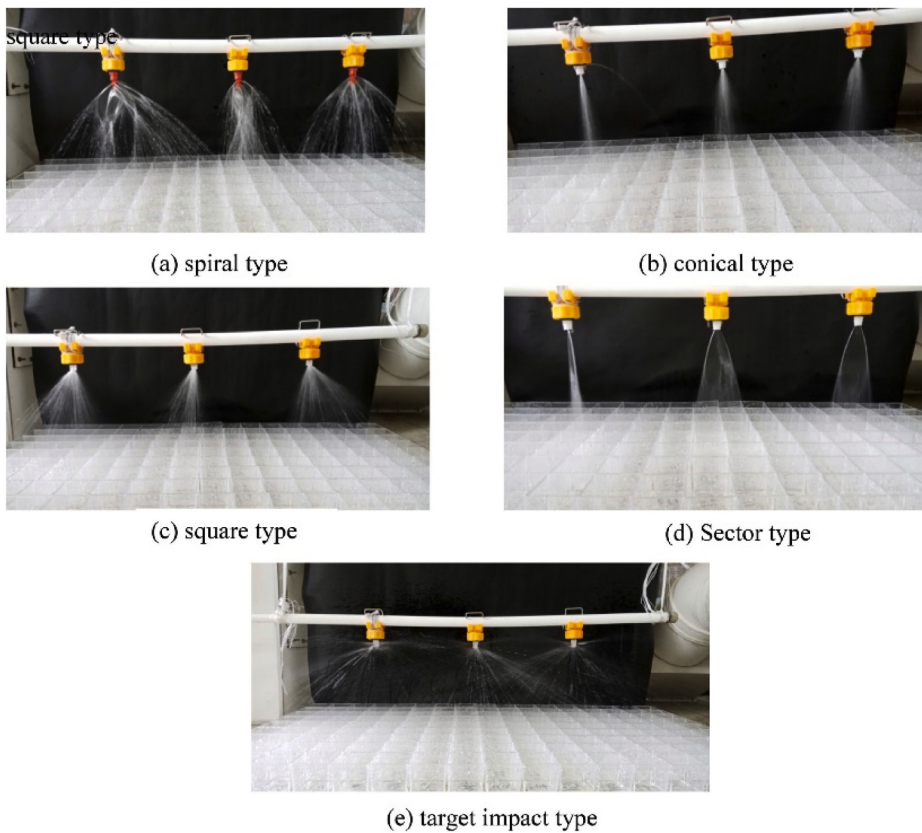


Fig. 18. Various spray nozzles (a) water distribution effect and (b) volume coverage ratio [77]. Reprinted with permission from Elsevier.

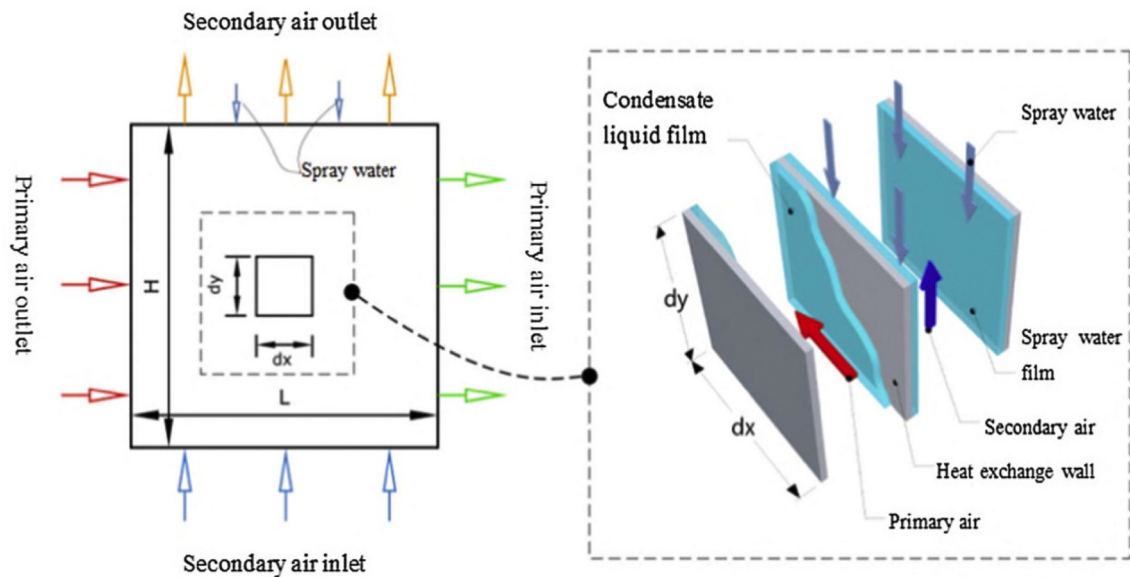


Fig. 19. Representation of the IEC model [60]. Reprinted with permission from Elsevier.

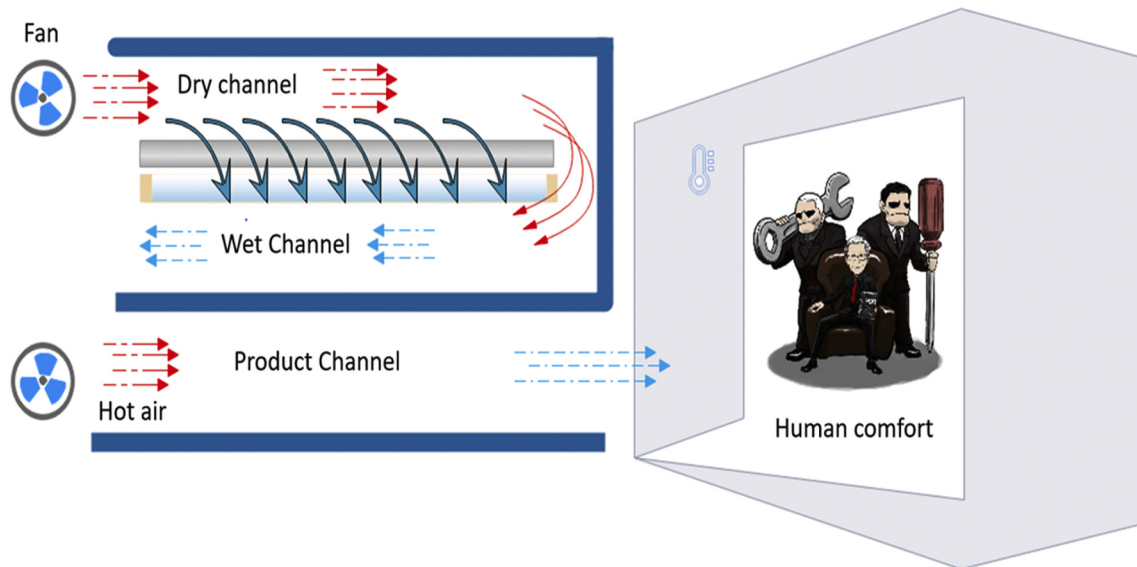


Fig. 20. Working principle of M-cycle.

potential especially for air conditioning in building application [36].

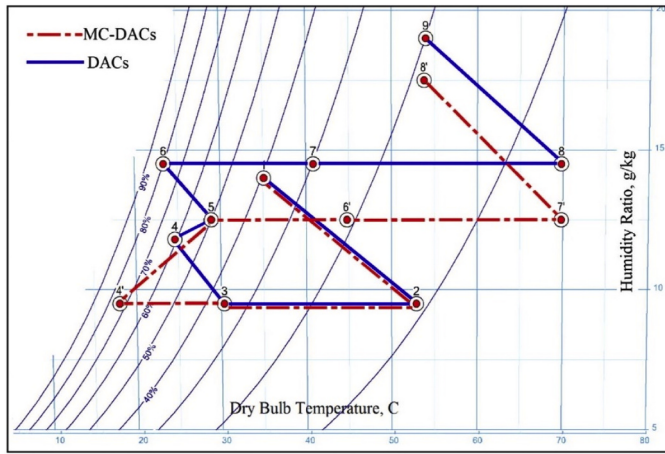
7. Effect of operating conditions on cooling performance of IECs

Operating conditions are important parameters to augment performance and effectiveness. Major operating parameters include primary and the secondary air stream, the channel width, the inlet relative humidity, and the wettability of the plate [103]. Zhao et al. [104] performed numerical analysis to study the effect of these operating parameters for higher cooling effectiveness (dew point wet bulb) and cooling capacity. He recommended design conditions for UK climate with wet bulb and dew point effectiveness of up to 130% and 90%, respectively. Anisimov et al. [105] performed numerical analysis on cross flow dew point evaporative cooler (D-IEC) and studied the effect of geometrical as well as operating conditions for higher effectiveness and specific cooling capacity. Khalid et al. [106] performed an experimental study on improved cross flow dew point evaporative cooler (D-IEC) with similar inlet conditions as that of Zhan et al. [107] and showed a better

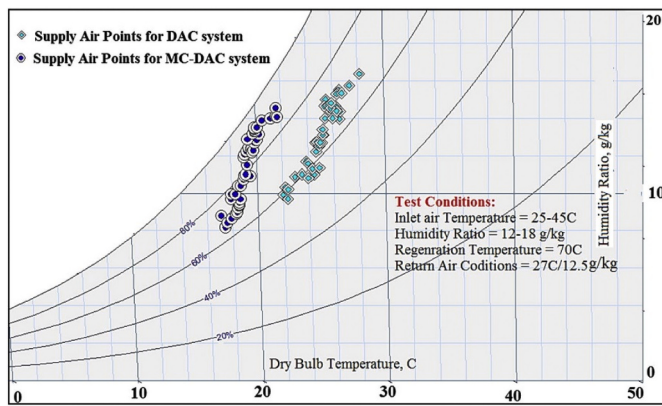
effectiveness value.

In general, the cooling (wet bulb and dew point) effectiveness increases at a higher inlet air temperature and a lower inlet humidity ratio. For inlet humidity of the dry channel air, there is no significant effect on the evaporative performance. However, for the wet channel, the effectiveness (cooling efficiency and COP at lower RH) increase at a lower humidity ratio. This is because at low values, the ability of air to absorb water vapor increases considerably. Hence, it required more latent heat for evaporating water on wet surface. Consequently, more sensible heat will be transferred from dry side to wet side. In most cases, the optimum design value is about 11.35 g/kg [106,108]. Higher inlet temperature and lower humidity values suggest that these indirect evaporative systems are better for dry and hot regions. For humid areas, a desiccant based evaporative cooler [42] can be used for better cooling performance.

For the influence of feed water temperature, it was found that the effect on cooling effectiveness is negligible [100,104,106,109,110]. In case of working to intake air ratio, the cooling effectiveness increases



(a)



(b)

Fig. 21. Conventional DAC and MC-DAC systems (a) psychrometric chart, (b) psychrometric chart for supply air [67]. Reprinted with permission from Elsevier.

with increasing ratio. It is due the fact that heat capacity and water absorption capacity is small at a lower mass flow rate of working air compared to primary air while it is high when the mass flow rate is higher than that of primary air. However, at higher values the supply airflow rate decreases. Cooling capacity and COP first increases with the increase of intake air ratio and then decreases with an optimum point of 0.3. In this regard, the compromised value between effectiveness and cooling efficiency is mostly in range of 0.3 to 0.65 [18,106,109].

Intake airflow rate reflects the air velocity across working and product channel. Reynolds number and Nusselt number are greatly influenced with inlet air velocity, thereby showing major impact on heat and mass transfer between two adjacent air streams. Cooling capacity increases at a higher inlet air velocity but the cooling effectiveness increases at a lower velocity which may result in lower supply air temperature. This is due to the fact that the contact time between air and wet surface increases and as a result more evaporation rate occurs. The sensitivity of cooling effectiveness with change of velocity is very low as compared to that of cooling capacity. Cooling capacity can be improved at higher velocity at the expense of insignificant increase of supply air temperature. In addition, lower COP occurs when pressure drop is increases at a higher velocity. Therefore, for higher cooler effectiveness and COP, the inlet air velocity must be small. In most cases inlet velocities less than 1.5 m/s are suggested as the optimum values with higher cooling effectiveness [104,107,110].

8. Effect of geometry on cooling performance of IECs

Channel height, length and shape are three major geometric parameters for configuration of heat exchanger. Geometric parameters have important impact on cooling performance of evaporative coolers. Channel geometry affects the channel hydraulic diameter and the surface area to facilitate heat transfer. Therefore, the flow pattern and flow rate changes, which in turn influences the heat and mass transfer rate and cooling capacity of the exchangers. With the increase of channel height, both the cooling effectiveness and cooling capacity decreases while COP and output air temperature increases. However, small channel height results in higher flow resistance and eventually deteriorates the energy efficiency. Cui et al. [108] studied the separate effect of product and working channel height. They used a new channel height ratio to characterize the performance and the ratio is defined as

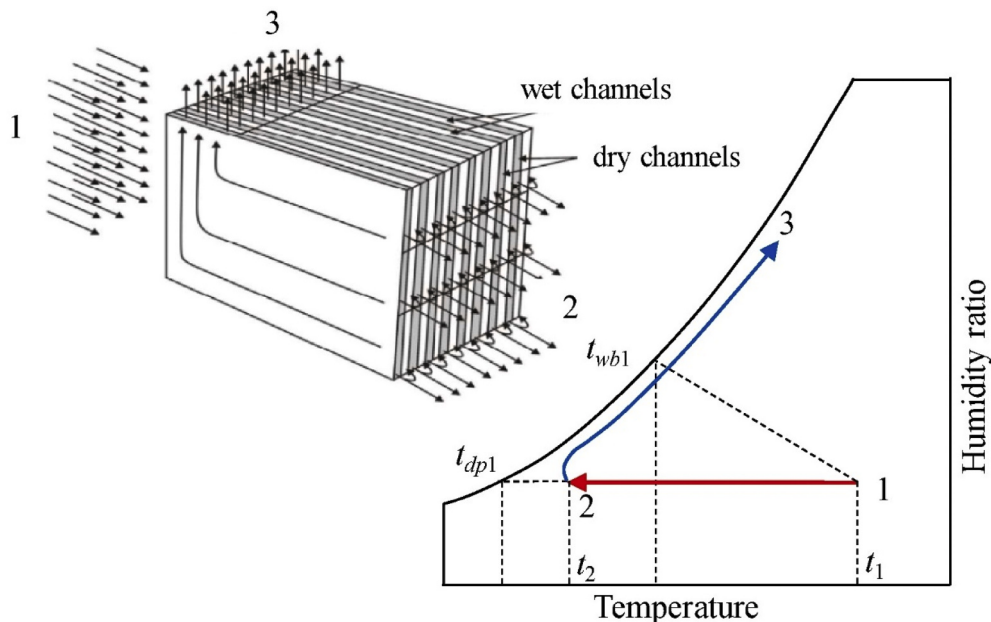


Fig. 22. Illustration of the C-D-IEC system [58]. Reprinted with permission from Elsevier.

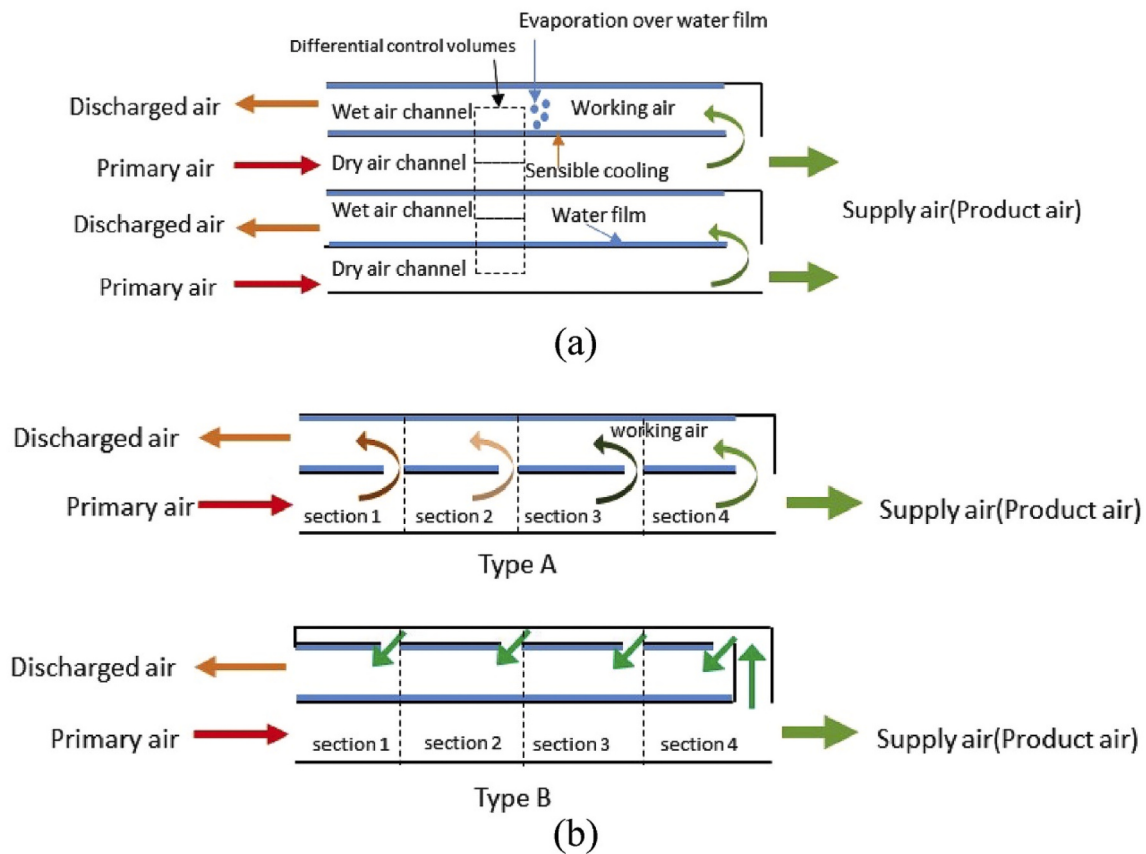


Fig. 23. Representation of the proposed D-IECs configurations: (a) single-purge, (b) four-purge [49]. Reprinted with permission from Elsevier.

the ratio of working channel height to the half of the product channel height. They found that the effectiveness reaches maximum if the ratio is equal to one, suggesting the product channel height is equal to the half of working channel height. For acceptable effectiveness and efficiency, the optimum value for height ranges from 5 to 6 mm [1,102,105,107,108,110,111]. Channel length corresponds to longer contact time and area. Therefore, heat and mass transfer rate is highly dependent on channel length. Cooling effectiveness and cooling capacity increases with the rise of dimensionless length (length/height). However, beyond certain value, the increasing rate slows down while the pressure drop still increases dramatically with larger channel length. As a result, the recommended dimensionless length is at least 200 [102,107,108,110,111]. Corrugated surfaces contain more surface area to fulfil heat and mass transfer. Pandelidis et al. [112] performed a comparatively numerical study on counter flow (R-IEC). They compared the performance of four different channel shapes including rectangular, square, triangle and flat. Results showed that triangular shape achieved the highest effectiveness for its largest surface area. However, thermal efficiency of flat channel was close to that with triangle channel. Anisimov et al. [105] numerically compared flat, square, and triangular shapes of channel. They suggested that if the heights of channels were maintained to be minimum, the triangular shapes would provide a better effectiveness as compared to flat channel.

Among different HVAC systems such as the datacenter applications, particular attention to enhance energy efficiency by using the IEC systems to release the compressor loading is quite imperative. This is also noted as the free cooling as depicted by Daraghme and Wang [113]. The performance relies on the sufficient water-layer formation on the heat-exchange plates. Hence, an efficient system for promoting the water spreading alongside the heat transfer surface is imperative. Different geometries subject to parallel-flow and counter-flow arrangements of water and air with IEC have been experimentally investigated

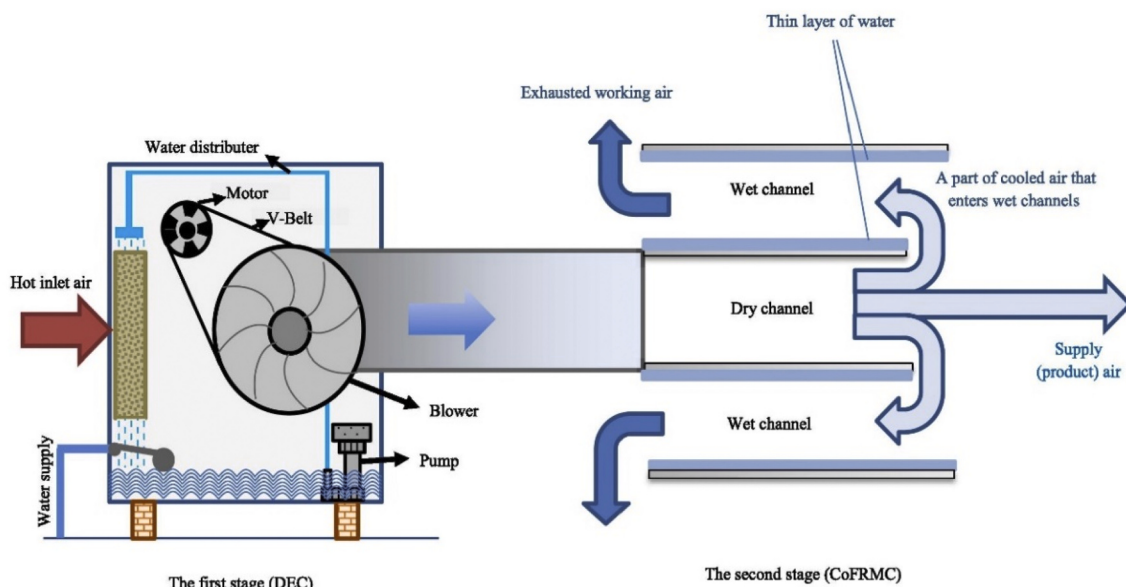
[72] which highlight the strong influence of plate geometry on the heat transfer and surface wettability. A protrusion of reticular plates tends to be more effective. Compared to the counter-flow arrangement, the parallel water and secondary air flows configuration results in increased wet bulb efficiency and reduced pressure drop.

In most of the studies, flat channels have been used because it is easy to construct while construction of evenly triangular channel are comparatively harder to construct. Likewise, even distribution of water is another problem associated with corrugated channel [105,112]. Recently, Kim et al. [114] developed regenerative evaporative cooler (R-IEC) with triangular shapes for both dry and wet channels by using new humidifying material made of cellulose and PET. Cellulose helps to spread the absorbed water in paper while PETs provide stiffness to retain the shape and corrugation. They experimentally analyzed the moisture transfer and pressure drop characteristic of such design and obtained better effectiveness of IEC units with triangular channels.

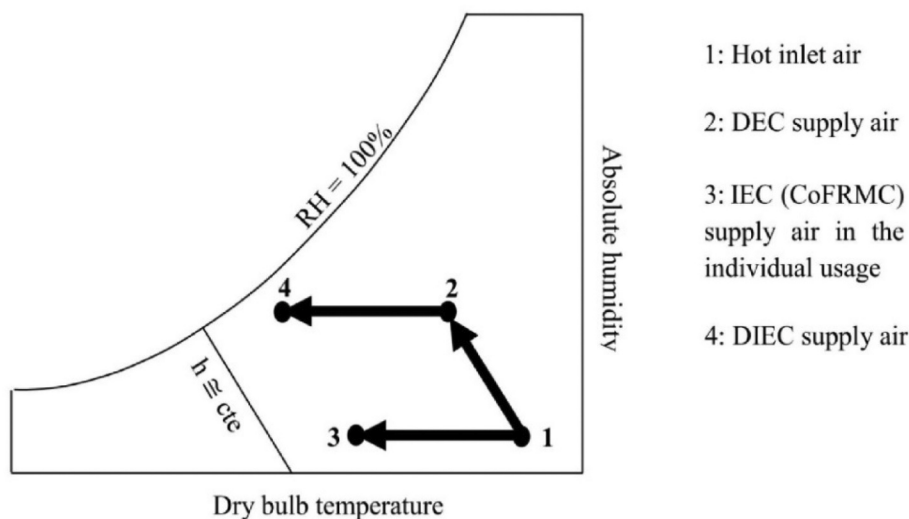
9. Effect of materials on cooling performance of IECs

For indirect evaporative cooling system, the evaporative material properties i.e. its evaporation ability, moisture absorption ability and diffusivity, have greater impact on cooling efficiency and performance of the system. In the wet channel of IEC, an evaporative material layer is needed that can evenly distribute and hold the water along entire area. That will increase the contact area between the working air and wall and as a result, a better sensible heat exchange can occur between dry channel and wet channel. An efficient material should contain characteristics like effective heat and mass transfer, low-pressure drop, inexpensive, avoiding bacteria growth and can be developed in different geometries.

Several attempts have been done for development of efficient and sustainable evaporative material for enhancing the performance and



(a)



(b)

Fig. 24. (a) Two stages direct-indirect evaporative cooler (C-D-IEC); (b) psychrometric representation of the process of DEC, IEC (CoFRMC) and DIEC [69]. Reprinted with permission from Elsevier.

cooling potentials of evaporative cooling systems. Evaporative materials can be classified as metals, ceramics, fibers, zeolite, and carbon type. Zhao et al. [115] performed a comparative study on all these evaporative materials and concluded that the thermal properties of materials impose very low impact on heat and mass transfer efficiencies of exchanger. Instead, shape formation/holding ability, durability, compatibility with water-proof coating, contamination risk as well as cost, are more important factors to be considered. For materials with fibers can offer good water permeability so that a better evaporation rate can achieve. Fiber types include cellulose, palash, coconut, Jute tossa, luffa ground, Aspen, Kraft, and NSSC type. Many researchers have investigated the performance of fibers [116]. Jain [117] performed an experimental analysis on coconut fibers and palash fibers and compared

the performance with aspen and khus fibers. Reza et al. [118] developed an experimental setup to analyze the performance of cellulosic pads. Results showed that for velocity of 1.8 m/s and a thickness of 150 mm, pad 5090 showed maximum efficiency while pressure drop was high for pad 7090 at same conditions. Kulkarni and Rajput [119] performed a comparative analysis on evaporative cooling pads of different configuration and materials. Rectangular, cylindrical and hexagonal configurations with rigid cellulose, aspen, corrugated paper and high-density polyethylene were analyzed. Hexagonal pad with aspen material showed a 91% highest saturation efficiency while the lowest value of 72.4% was obtained for rectangular pad of cellulose material.

Maurya et al. [120] experimentally compared the saturation efficiency and cooling capacity of cooling pad made of cellulose, aspen fiber

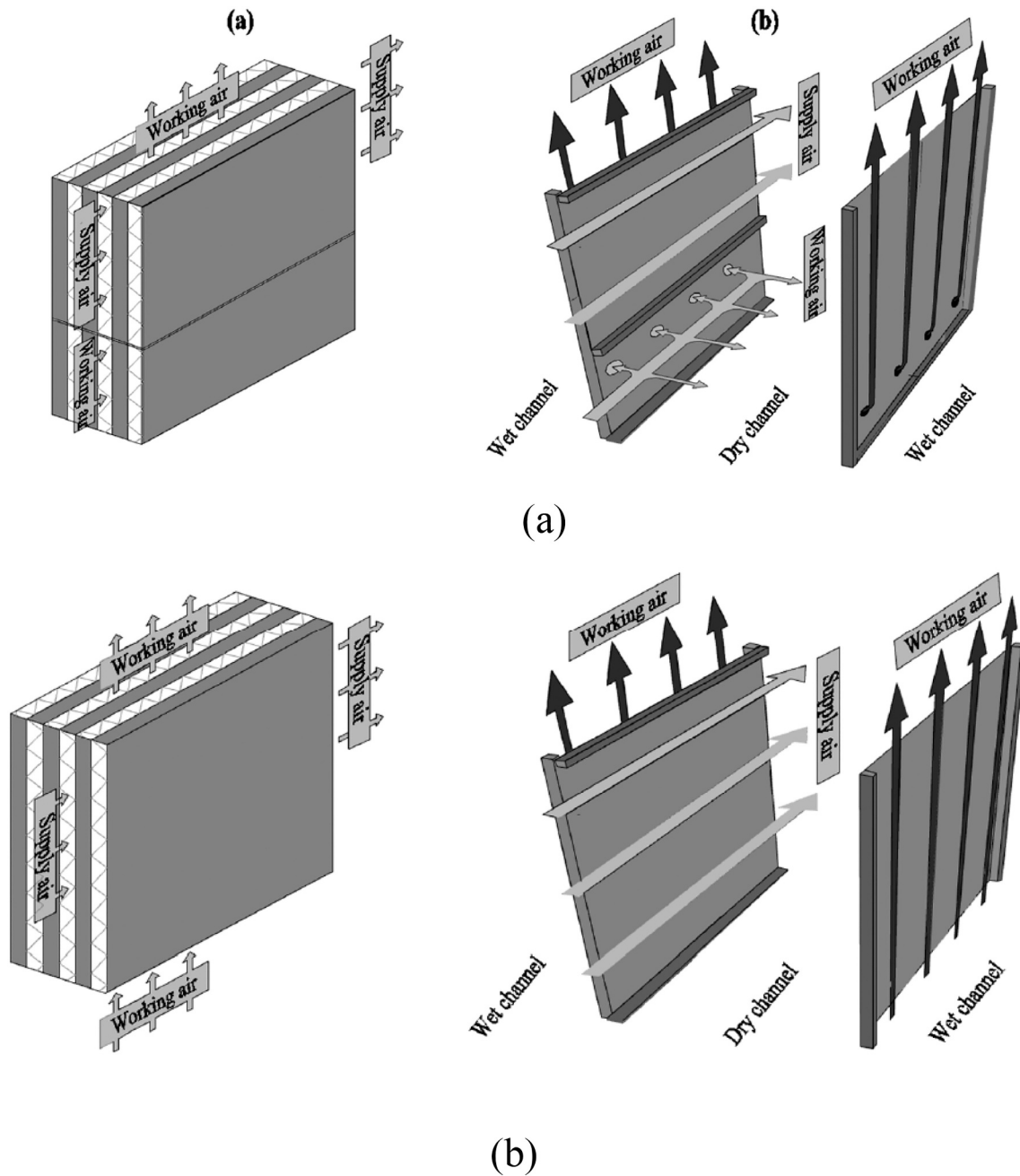


Fig. 25. Schematic and air flow in the channels for C-D-IEC in case of (a) regenerative HMX, (b) conventional HMX [57]. Reprinted with permission from Elsevier.

and coconut coir. Results showed that at 0.5 m/s air velocity aspen has highest saturation capacity of 80.99% while cellulose with 69.58% and coconut coir with 68.15%. Coconut coir performance was almost same as that of cellulose. In an experimental study [114], an attempt was made to analyze the moisture transfer and pressure drop characteristics of new developed samples made of cellulose and PET while using Glasdek. Results showed a better moisture transfer and a lower pressure drop over commercially used Glasdek material.

Recently Xu et al. [121] performed an experimental analysis on 6 different fabric samples and compared it with commercially available Kraft paper. Based on their tests i.e. absorption ability, wetted area, diffusion rate and evaporation rate, they found that 2 samples (Coopass® bird eye mesh fabric and Bamboo charcoal®pCoolmax active fabric) have increased vertical absorption rates of 182% and 171%, diffusion rates of 14% and 37% and evaporation rates of 20% and 14% respectively higher than that for commonly used conventional Kraft

paper. Cloth fabrics are commonly available commercial materials which have low pressure drop, durable and can be easily shaped into different geometries. They resist bacteria formation in wetted areas and are very thin to facilitate effective heat transfer. Therefore, cloth fabrics are highly effective material for evaporative cooling purpose. However, due to non-rigid behavior they can be attached with rigid sheets of highly conductive materials like aluminum for wet channel formation in indirect evaporative coolers.

10. Conclusions

Indirect evaporative cooling with regenerative modification has become an advancing trend in air conditioning research field. System design and operating conditions are important for development of product. In this paper, a detailed review has been conducted on recent developments in the indirect evaporative cooling (IEC) systems as well

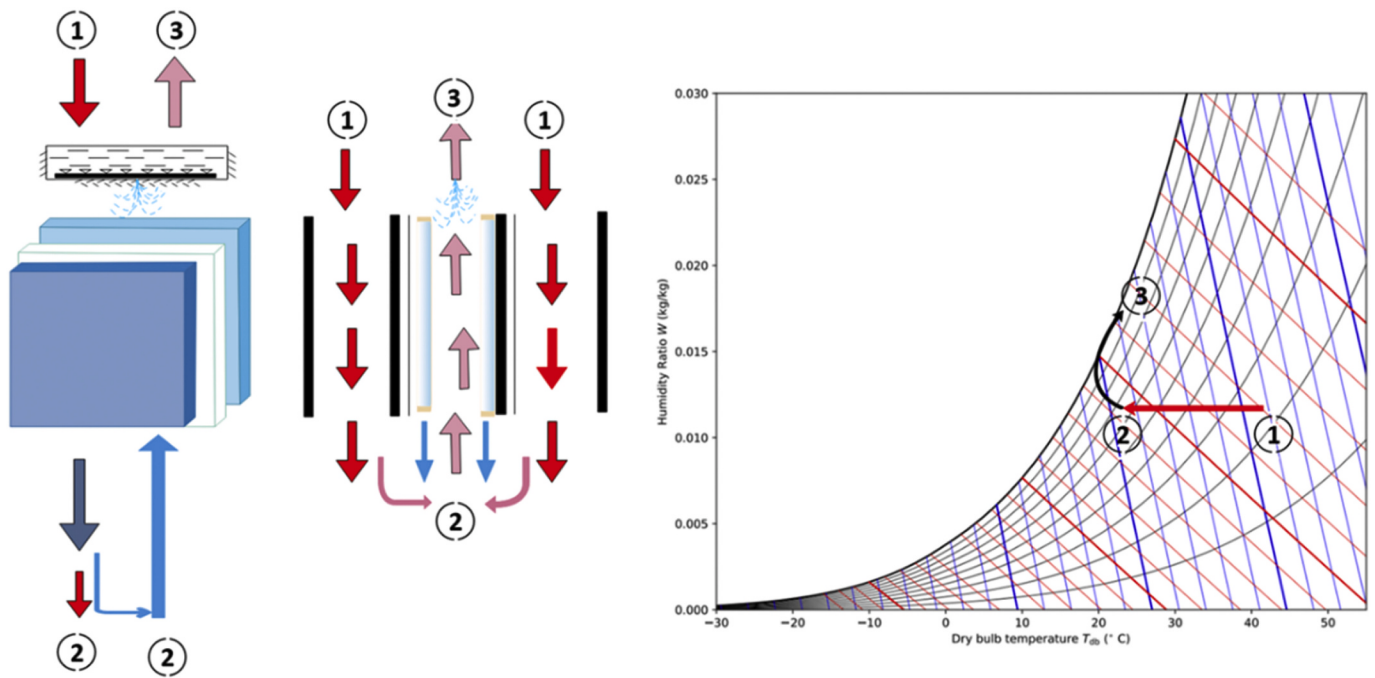


Fig. 26. Regenerative Indirect evaporative cooling.

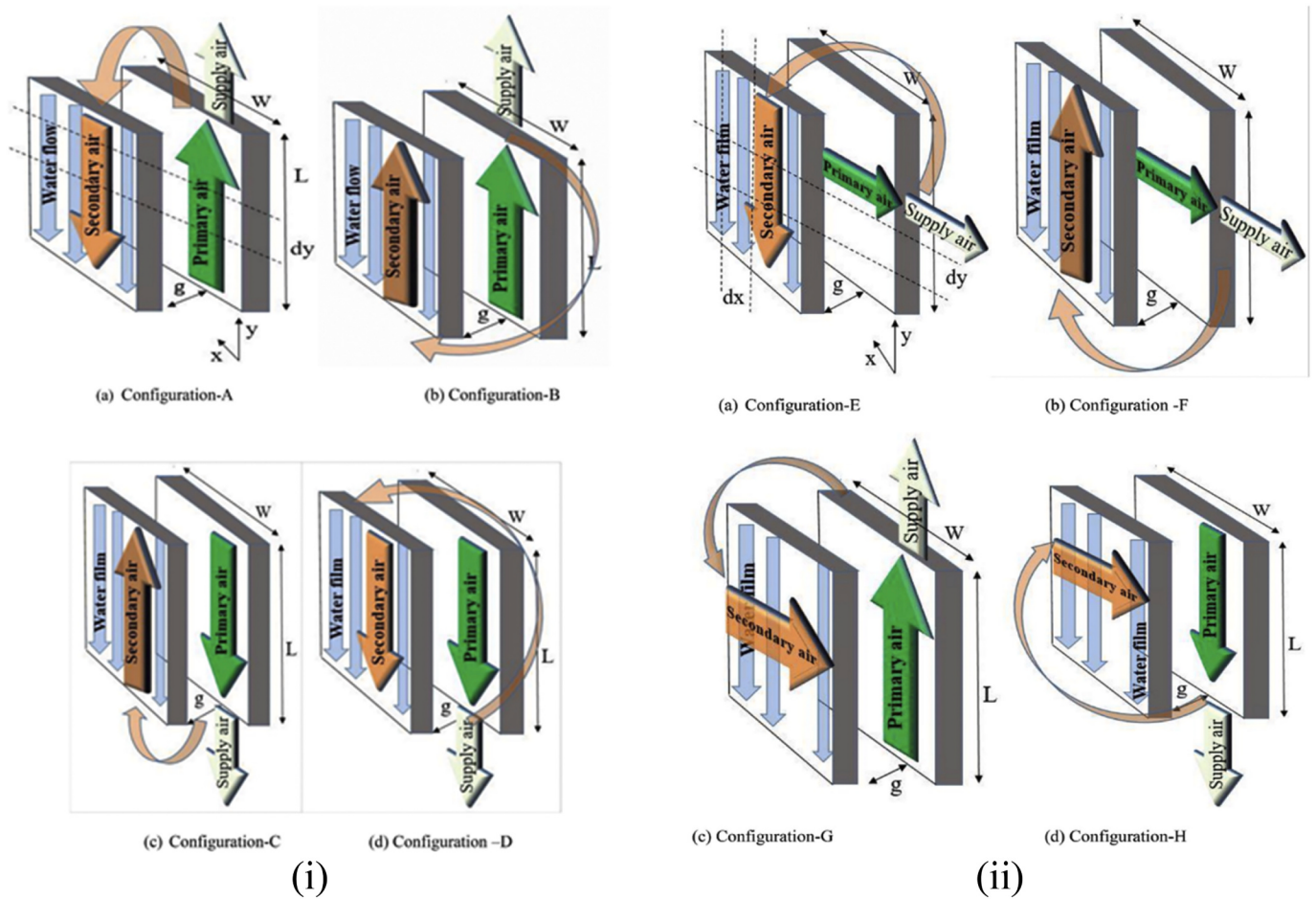


Fig. 27. Different configurations of a regenerative (i) parallel/counter flow evaporative cooler, (ii) regenerative cross-flow evaporative cooler [48]. Reprinted with permission from Elsevier.

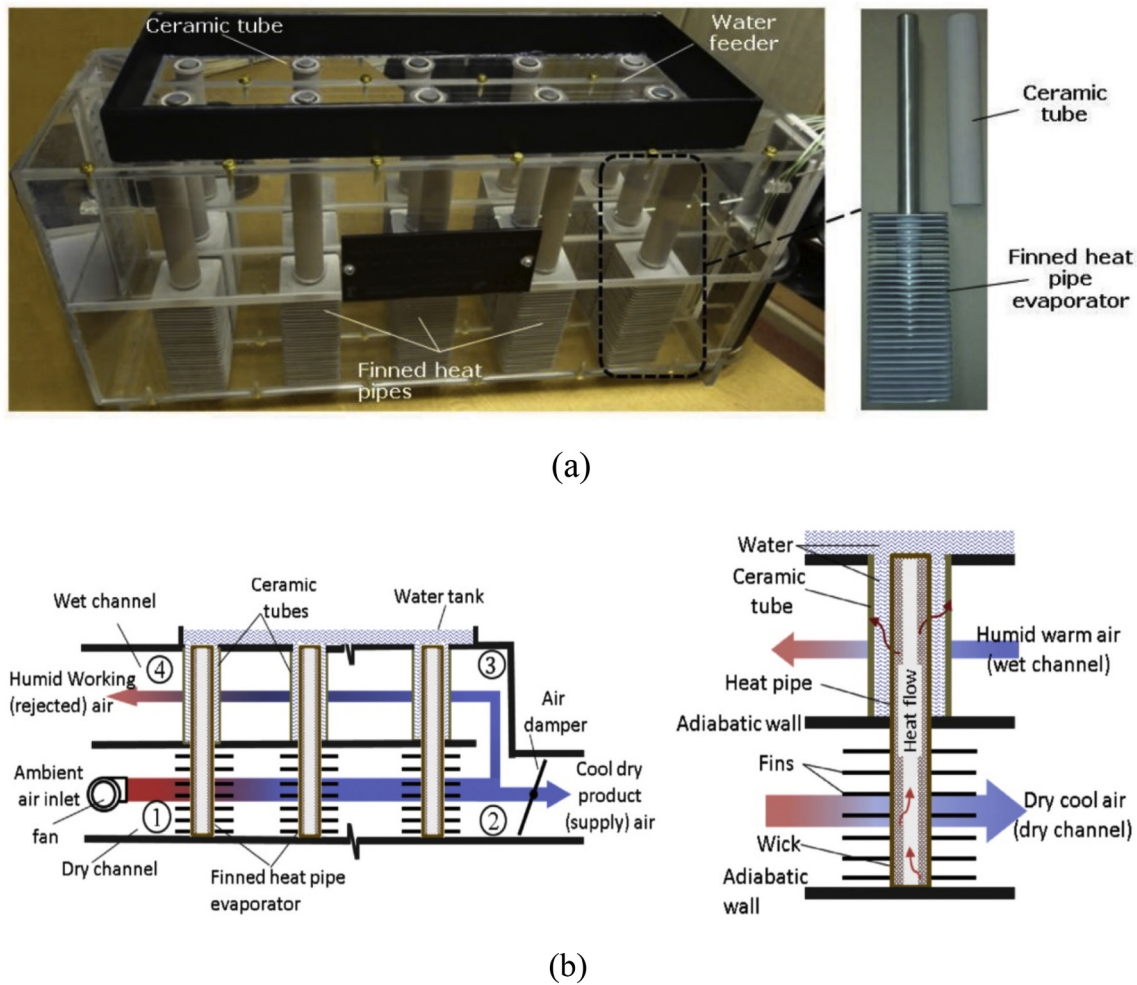


Fig. 28. (a) Regenerative cooler assembly along with heat pipe-ceramic tube, (b) working principle and configuration of cooler (right) along with heat pipe-ceramic tube system [64]. Reprinted with permission from Elsevier.

as their associated design parameters and operating conditions for higher cooling effectiveness and cooling capacity. The current review also consolidates the design and performance of various indirect evaporative cooling systems (such as classical indirect evaporative cooler, regenerative, dew point cooler, and Maisotsenko cycle based cooler). Furthermore, integration of these indirect evaporative cooling systems with other cycles and applications is elaborated. It is found that major design parameters include system configuration, inlet airflow conditions, channel geometry, and evaporative material. Some major results from this review is given in the following:

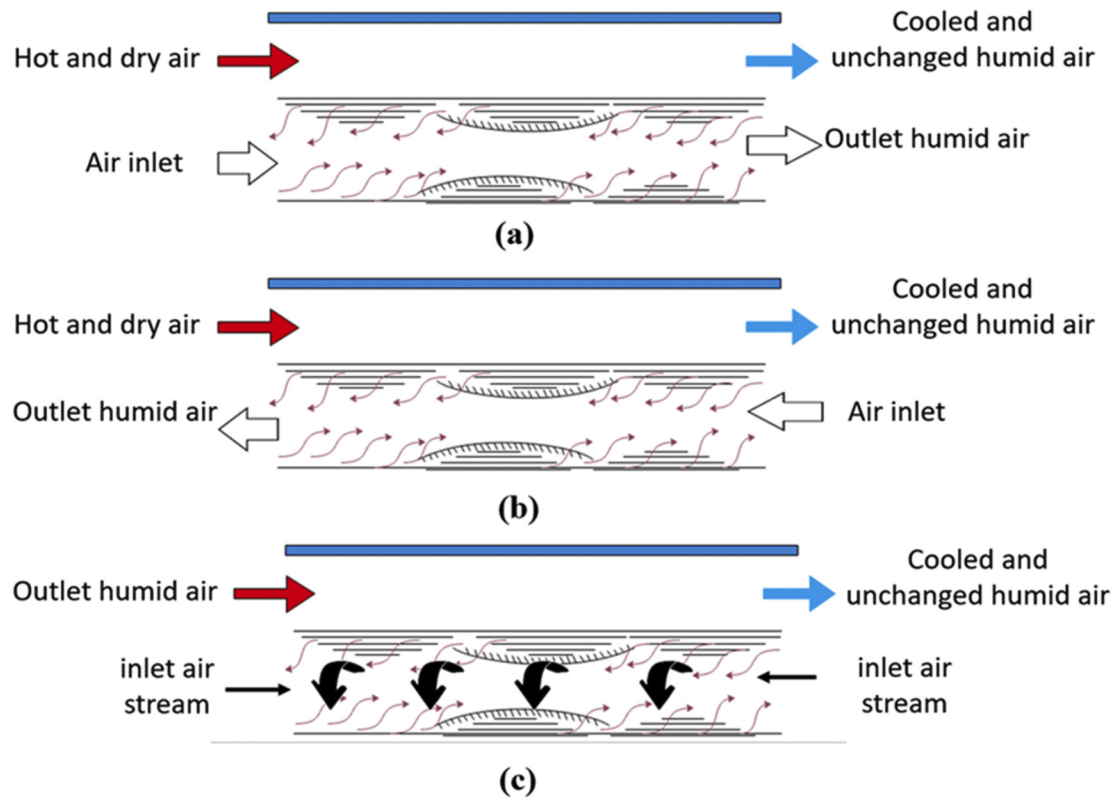
- Counter-flow arrangement is more effective than the cross-flow arrangement due to higher cooling effectiveness, cooling capacity, and system compactness.
- At a higher inlet air temperature and a lower humidity ratio (i.e. less than 11.35 g/kg), the system provides a higher cooling effectiveness.
- Feed water temperature has insignificant effect on evaporative cooler performance.
- Intake air velocity must be small, and it is recommended to be less than 1.5 m/s for higher cooling performance.
- Working intake air ratio must be in range of 0.3 to 0.65 to compromise between cooling capacity and cooling effectiveness.
- Lower channel height i.e. 5 to 6 mm and higher channel length (dimensionless length at least 200) and triangular shape of channel provide better system cooling performance.

- Fabric material has more cooling potential for indirect evaporative cooler due to high heat and mass transfer ability, low cost, contamination resistance, and low pressure drop characteristics.
- Hybrid systems such as indirect evaporative cooling system with other cycles have great potential for energy saving.
- Evaporative cooling systems can be a potential solution of thermal management in various non-human applications such as agricultural storage, poultry, and livestock.

Despite of substantial progress in development of the IEC technology, numerous inherent hitches still stay with this topic such as less temperature reduction capabilities, low cooling effectiveness, dependency on the environmental conditions, and large geometrical size requirements. These limitations have been tried to eliminate by integrating IEC systems with other cycles. More efforts are required to evaluate the cooling capability of various hybrid systems (such as IEC incorporating fan coil units, air handle units, cooling towers for chilled water making, solar driven desiccant cycle, and Rankin cycle based power generation system) in different cooling applications. More empirical, semi-empirical, and data driven models need to be developed for assessment and optimization of the cost effective evaporative cooling systems.

Credit author statement

Uzair Sajjad: Conceptualization, Methodology, Writing.



DEC	IEC	Dew-point	Energy recovery IEC
Limited by wet bulb of treated air	Limited by wet bulb of treated air	Limited by dew-point of treated air	Limited by wet bulb of exhaust air
Humidifies supply air	Does not humidify supply air	Does not humidify supply air	Dehumidifies supply air
Flow arrangements			
	Parallel-flow (not used)	Counter-flow (regenerative)	Cross-flow
	Cross-flow	Cross-flow (M-Cycle)	Counter-flow
	Counter-flow	Multistage	

(d)

Fig. 29. Different types of indirect evaporative cooling systems based on dry to wet channel flow arrangement: (a) Parallel flow, (b) counter flow, (c) cross flow, and (d) different system configurations of IECs.

Naseem Abbas: Data curation, Methodology, Writing.
 Khalid Hamid: Data curation, Methodology, Writing.
 Saleem Abbas: Data curation, Methodology, Writing.
 Imtiyaz Hussain: Data curation, Methodology, Writing.
 Syed Muhammad Ammar: Data curation, Methodology, Writing.
 Muhammad Sultan: Reviewing and Editing.
 Hafiz Muhammad Ali: Supervision and Reviewing.
 Muzamil Hussain: Writing and Editing the revised manuscript.
 Tauseef-ur- Rehman: Writing and Editing the revised manuscript.
 Chi- Chuan Wang: Supervision and Reviewing.

Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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